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*INVESTIGATION OF NUCLEAR
MOISTURE-DENSITY METERS*

(REPORT ON FIELD STUDY)

JUNE 1964

NO. 14

*Joint
Highway
Research
Project*

*PURDUE UNIVERSITY
LAFAYETTE INDIANA*

by
T. G. WILLIAMSON



INVESTIGATION OF NUCLEAR MOISTURE-DENSITY METERS

TO: K. B. Woods, Director
Joint Highway Research Project

June 19, 1964

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 6-10-5
Project: C-36-16E

Attached is a report summarizing the field work accomplished on the Nuclear Moisture-Density Project. This report was prepared by Mr. T. G. Williamson.

In addition to the field data, pertinent data from the laboratory study are included in this report. Recommendations regarding the use of the instruments by the Indiana Highway Commission are also included. This is the final report for this project.

Copies of the report should be transmitted to the Bureau of Public Roads. Mr. Preston Smith and Mr. Walter T. Spencer should also receive copies for review.

Respectfully submitted,

Harold L. Michael
Harold L. Michael, Secretary

HLM:bc

Attachment

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Final Report
INVESTIGATION OF NUCLEAR MOISTURE-DENSITY METERS

(Report on Field Study)

by

T. G. Williamson
Graduate Assistant

Joint Highway Research Project

Project: C-36-16E

File: 6-10-5

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Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with

Indiana State Highway Commission

and the

Bureau of Public Roads
U.S. Department of Commerce

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or the
Bureau of Public Roads

Purdue University
Lafayette, Indiana
June 19, 1964

INVESTIGATION OF NUCLEAR MOISTURE-DENSITY METERS

(Report on Field Study)

INTRODUCTION

On August 9, 1961, the Joint Highway Research Project Advisory Board approved a plan of study entitled "Investigation of Nuclear Density and Moisture Meters" (1). The purpose of the original study was to investigate the use of a commercially available moisture-density meter for possible use by the Indiana State Highway Commission. It was desired to determine the feasibility of using such an instrument in compaction control to complement or replace the more conventional sand replacement method of determining density.

The initially proposed project became effective on September 1, 1961 and was approved by the Joint Highway Research Board, the Indiana State Highway Commission and the Bureau of Public Roads as a cooperative study using HPS funds. It was decided at that time to test only one commercially manufactured instrument.

On February 14, 1962 a revised plan was approved. This plan was an expansion of the original plan in that three different commercial instruments were to be tested and a comparison made to determine advantages and disadvantages of the various systems as would pertain to their use in highway construction.

The work on this project has been carried out by personnel of the Soils Laboratory, Joint Highway Research Project. Progress reports submitted on this project include a report prepared by Burgers (2), a paper by Burgers and Yoder (3), a staff report (4) and a report by Witczak (5).

REPORT OF THE COMMISSIONER

INTRODUCTION

The National Archives and Records Administration (NARA) is pleased to present this report to the public. This report provides a comprehensive overview of the activities of the NARA during the year 1999. The report is organized into four main sections: Administration, Programs, Financial Operations, and General Information. The Administration section provides information on the organizational structure of the NARA, including the Office of the Commissioner and the various offices and divisions. The Programs section describes the major programs and activities of the NARA, including the preservation and access programs, the records management program, and the public services program. The Financial Operations section provides information on the budget and financial performance of the NARA. The General Information section provides information on the NARA's mission, vision, and values.

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The progress reports summarized laboratory calibration of the instruments hereafter referred to as Instruments A, B and C. Burgers work was concerned with the influence of selected material properties on the determination of density and moisture content by nuclear methods. He was also concerned with the depth of penetration of the different gauges and studied this effect for instruments A and B through the use of heavy liquids.

Witczak's work dealt primarily with the effect of substrate material properties, instrument stability and procedural factors on density and moisture determinations using nuclear methods. His research was confined to the laboratory and involved only Instruments A and B.

In the original plan of study, it was proposed that extensive studies be made of the instruments in the field under construction conditions. This testing was to be carried out on base course and subgrade materials and the results compared to those obtained by conventional testing practices.

This report primarily summarizes the field work conducted during the summer of 1963. For comparative purposes, however, some of the data obtained in the laboratory study are included in the report.

The results and conclusions at the end of the report are based upon the results of the combined laboratory and field studies. This report is the final report for this study.

PURPOSE AND SCOPE OF FIELD STUDY

The purpose of the field study was to determine if the instruments could be used as field devices to control compaction in much the same manner as the sand replacement method is presently used. Calibration curves for both the density and moisture gauges for each instrument were to be obtained and compared to those previously obtained from laboratory

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DOES hereby certify that the within and foregoing is a true and correct
copy of the original as the same appears in the records of the
Court.

It is not possible to give a simple answer to this question. The answer depends on the specific situation and the individual involved. In some cases, a person may be able to return to work after a short period of rest. In other cases, a person may need to take a longer period of time off work. It is important to consult with a doctor or other healthcare professional for advice on when it is safe to return to work.

investigations in order to determine if laboratory calibration curves could be used for field determinations. Also, the three instruments were to be compared to determine if one instrument or another was better suited for the field work encountered.

The calibration curves were to be obtained by performing a standard sand replacement-density test and moisture determination on the same test location as the various nucleargauges were employed and to plot the sand density or field moisture content versus some function of the count obtained from the nucleargauges. This procedure will be discussed in more detail later in the report.

During the laboratory calibration study of the instruments, material type was found to play a major role in arriving at a density calibration curve for each instrument. Different materials seemed to give separate density calibration curves such as is shown by Figure 1.* However, the exact effect of material type was not known. Further studies were made by Witczak (5) using a selected crushed limestone and crushed quartzite. From the results obtained using these materials (see Figures 2 and 3 for Instruments A and B), it was deduced that a large proportion of the deviation between the density calibration curves for these materials was due to the differing mass absorption coefficients. The mass absorption coefficient used corresponded to the major constituent of each material, namely, calcium for the limestone and silicon for the quartzite.

On the basis of the above, it was felt that the effect of mass absorption coefficient should be investigated in the field. To arrive at some means of measuring this phenomena of material effect in the field,

* All figures and tables are in the appendix at the end of this report.

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will be found in the appendix of the report of the
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without performing a complete chemical analysis of each soil, it was decided to use pH of the soil as an indicator of soil type. From the laboratory study previously mentioned it was noted that the limestone was a basic soil and the quartzite an acidic soil and that pH could be used to distinguish between them.

Each instrument was employed in the study and soil pH was determined for each soil as an indicator of soil type. Both the moisture and density gauges were used in the field work.

MATERIALS

The materials involved in the field investigation covered a wide range of soil conditions and types. With the pH measurement being employed to distinguish between various soils it was decided that soils of an acidic, neutral and basic nature should be tested. Through talks with personnel of both the Bureau of Materials and Tests of the Indiana Highway Commission and the United States Department of Agriculture three general test sites were selected.

The test sites selected were located on the Interstate 69 construction project in Delaware County near Daleville, the Interstate 465 project at U. S. 31 just South of Indianapolis and Brown County State Park, Indiana.

The three general locations chosen provided the wide range in soil pH values desired along with a large variation of soil types and compactive efforts. The soil types tested included silts and clays of both high and low plasticity, granular materials used in subbases and granular-soil mixtures. Compactive efforts ranged from natural earth deposits such as found in Brown County State Park to subbases compacted to 100 percent standard AASHTO density. The test sites included natural ground areas,

compacted fills, cut areas, loose and compacted subbases, borrow pits and soil waste areas.

The wide range in soil conditions and pH values was desirable in order to obtain calibration curves over a wide range of densities and pH values. It was felt that possibly three calibration curves would result, one for each pH range of acidic ($\text{pH} \leq 6.9$) basic ($\text{pH} \geq 7.4$) and neutral ($7.3 \geq \text{pH} \geq 7.0$). These ranges were those recommended by the Agriculture Department as representative values.

EQUIPMENT

The equipment involved in the field investigation included the three instrument systems referred to as A, B and C and other assorted equipment to supplement these basic gauges.

Each nuclear instrument system consisted of a moisture and a density probe and a portable scaler. All of these are portable type backscatter gauges, and each gauge contains a radioactive source and detection system. The function of the scaler is to transfer pulses transmitted from either surface gauge into counts to be recorded on a series of glow tubes as the desired results. Further details of the equipment may be found in progress report No. 8, January 1963 (4).

Other equipment involved included a portable battery charger, a portable pH meter, a geiger counter used to check the radiation level of the gauges and all equipment necessary to perform a standard sand replacement density test and field moisture determination test.

All of the equipment was transported from test site to test site by a station wagon; foam rubber padding was used to protect the instruments from damage during transportation.

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It should be noted that both gauges of Instrument C suffered mechanical malfunctions of some nature during the first week of testing and no valid results were obtained with this instrument system. This instrument also had similar malfunctions befall it during the laboratory testing.

PROCEDURES OF TESTING

As each of the three general test areas was of a different overall nature, a reconnaissance of each test site was first made by the writer and Mr. Bob Rahn, representing the Indiana Highway Commission during the field study.

The test locations were chosen on the basis of overall conditions existing in the area, i.e. whether it was a cut or fill, highly compacted or loose and type of material. This was done to achieve a wide range in soil conditions that might affect the calibration curves.

After a test location had been chosen, a small area was leveled off on which the gauges were to be placed. The area prepared for each test was approximately two feet square and was leveled by using a piece of wood. Similar material from near the chosen test site and of a similar nature (see reference 2) was then passed through a No. 40 U. S. Standard Sieve and placed over the cleared area. Both the leveling operation and the placing of the thin ($1/4$ ") layer of filter material were done to insure proper seating of the gauges and to minimize airgaps under the instruments. It had been shown by Witczak (5) that the use of a filler layer produced a better calibration curve in that it tended to reduce scattering of the data.

The three instruments were then in turn used to measure both the moisture content and density of the soil at the prepared test site. While

one gauge was being employed in a test, the remainder of the radioactive sources or gauges were moved to approximately twenty to thirty feet from the test site to eliminate any effect of stray radiation upon the gauge being tested. This effect is shown by Figure 31 of progress report No. 8 (4).

The actual measurements made using the nuclear equipment were accomplished in the same manner as had been employed in the laboratory investigations. A brief description of the procedure is given in the following paragraphs.

A standard count reading was obtained both before and after each test. This count consisted of three one-minute readings from which an average was obtained. This was done using the air gap technique as described by Witczak (5). After taking the standard count reading, the gauge was placed on the test area and four one-minute readings were taken with the gauge being rotated through 180° between the second and third reading. This was done to insure that the average characteristic of the soil, whether it was density or moisture, was being measured by the gauge. These readings were then averaged to obtain the count for the substrate material and three more one-minute readings were taken using the standard air gap.

From the average of the two standard count readings and the average count on the substrate material, a relative count was obtained for each test site by dividing the substrate count by the standard count. This procedure was reproduced for each gauge used at each test area.

After obtaining the nuclear counts for all of the gauges at a test area, a standard sand replacement density test was made on this same soil. The test was performed in accordance with the specifications set forth

in publication TD-161C by the State Highway Department of Indiana, Bureau of Materials and Tests. A sample of this soil was then placed in an airtight moisture can and taken to the Bureau of Materials and Tests Soils Laboratory where a standard oven dried moisture content determination test was performed.

A sample of the soil was also placed in a glass beaker and distilled water was added to it to obtain a thin soil water slurry. This mixture was stirred thoroughly and a pH determination was made using the portable pH meter. In order to check the validity of these measurements, the assistance of personnel from the United States Department of Agriculture in Muncie, Indiana was enlisted. Personnel from that office performed several pH tests using the standard soil pH color charts as used by the Department of Agriculture and other organizations. These results were compared to pH values obtained using the pH meter. The results compared to within a value of one tenth in all cases. Check tests were also made by the writer using the color charts at various times during the testing to insure the validity of the pH values indicated by the pH meter.

Upon completion of the nuclear measurements, the standard density and moisture tests and the pH determination, a twenty to thirty pound sample was removed from the test area and these were then taken to the Joint Highway Research Project Soils Laboratory at Purdue. Classification tests were then performed on these samples in order to accurately identify and classify them.

RESULTS

The field testing program consisted of testing of the instruments at each test site following the procedure of testing previously described. The results of this testing are presented in the form of calibration curves

1. The first step is to identify the problem or goal. This involves understanding the current situation and what needs to be achieved.

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for each instrument. It should be noted that the calibration curves for Instrument A were determined using the least squares fit method. The calibration curves for Instrument B are represented by lines fitted "by eye." No calibration curves are presented for Instrument C due to a lack of data caused by malfunctions of the gauges.

Instrument "A"

A total of fifty-nine density tests and fifty-two moisture tests were performed using Instrument A. The materials tested covered a wide range of soil conditions and pH values.

Sand cone densities were determined at each test site and correlated with the nuclear counts to give calibration curves based on the sand cone measurements of density. The sand cone density was plotted against the relative count obtained by the nuclear gauge.

The use of the relative count procedure of plotting was chosen to reduce scattering of the data and to compensate for the variability of the standard count from test to test. It has been shown by Witczak (5) that the use of the relative count does produce a more uniform calibration curve with less scattering of the data points than is obtained by plotting actual counts against the bulk density. The variations of standard readings for both the density and moisture gauges for Instrument A are shown on Figure 4 along with the reliable error associated with each gauge. The reliable error was determined from Figure 5 which indicates reliable, standard and probable error levels associated with radiation intensity.

It can be seen that all of the moisture standards fell within the reliable error limits and that all but five of the density standards were within limits. This indicates that the gauges were operating satisfactorily

[illegible]

throughout the testing period and that the use of the relative count procedure is justified as the variations from test to test were relatively small in magnitude.

Figure 6 indicates all of the density data obtained during the testing period. The data are represented by overall general material type along with being placed in ranges of pH values. From these data, it was observed that possibly three distinct calibration curves should be drawn for the density gauge; these are shown on Figures 7, 8 and 9.

Figure 7 shows the calibration curve for soils with pH values greater than or equal to 7.3. The calibration curve for soils tested whose pH value was less than or equal to 7.2 is shown on Figure 8. In both cases the data points plotted are represented by symbols corresponding to the Unified Soil Classification System and it can be seen that soil type as defined by this classification procedure has no apparent effect on the calibration curves.

Also indicated on Figures 7 and 8 along with the calibration curve are dashed lines. These lines represent limits of ± 3 pounds per cubic foot of bulk unit weight variance from the solid line calibration curve. This value was arbitrarily selected as a common amount of variation which would be tolerable on compaction control of subgrade and base course materials. This figure of ± 3 pounds per cubic foot of density is also reported in the Colorado Department of Highways report on "Nuclear Testing Applied to Compaction Control" (6) as being within reliable limits.

From the figures it can be seen that approximately 80 percent of the test data points fall within the above specified limits. It should be noted that the destructive method of determining density by the sand cone method is in itself prone to variation in results. This is especially

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true in the case of granular materials where it is very difficult to prepare a test hole with smooth sides and of a uniform nature. Also, it is known that two people performing the sand replacement test on the same soil will not obtain identical results and that some variation is to be expected. Therefore, since the test to which the nuclear count is correlated is itself less than perfect, the results of 80 percent of the data within a range of ± 3 pounds per cubic foot for density seems to represent a reasonable amount of error.

As was previously stated, it was expected that a calibration curve for each pH range; basic, neutral and acidic would result. However, from the field data it was found that pH values of 7.2 and 7.3 formed the dividing values for the calibration curves. These values were determined by plotting the field data and determining what pH value tended to divide the data into two broad groups. The values of 7.2 and 7.3 are the middle values of what is commonly assumed to be the neutral range of pH, but all values equal to or greater than 7.3 are basic and less than or equal to 7.2 are acidic values, as assumed by the writer.

A comparison of the laboratory curves for limestone and quartzite and the field curves for the two pH ranges defined by the data is presented on Figure 9. As is observed, the field curves are approximately parallel as are the laboratory curves, but the laboratory curves are farther apart than the field curves. This difference in offset is attributed to the fact that the laboratory soils were pure limestone and quartzite materials and the field soils are a combination of different minerals and the pH difference is not as pronounced as would be measured on the pure laboratory materials.

Reference is made to Figure 1 which shows the effect of differing material types on the results of the density gauge as obtained in the

1. The first step in the process of identifying a problem is to define the problem. This involves identifying the symptoms of the problem and determining the scope of the problem. Once the problem has been defined, the next step is to identify the causes of the problem. This involves identifying the factors that are contributing to the problem and determining the relationships between these factors. Once the causes of the problem have been identified, the next step is to develop a plan of action. This involves identifying the steps that need to be taken to address the problem and determining the resources that will be needed to implement the plan. Finally, the last step in the process is to implement the plan and monitor the results. This involves putting the plan into action and tracking the progress of the implementation. Once the plan has been implemented, the next step is to evaluate the results and determine whether the problem has been solved. If the problem has not been solved, the process may need to be repeated.

laboratory. It can be seen from this graph that possibly three parallel calibration curves could be constructed and these are as indicated.

Although no measurements of pH were made for these soils, the possibility that the coarse sand is basic and the sand-soil mixture is acidic exists, and this would bear out the idea of a calibration curve for each general pH range. Also shown is a calibration curve for the sandy gravel which would correspond to the granular materials found in the field. These granular materials are discussed in the following paragraphs and tend to have their own individual calibration curve.

Figure 10 represents the calibration curve for granular materials tested during the field study. These materials tended to be unique in comparison to the soils and therefore required an individual calibration curve. This curve is seen to be steeper and to the right of the calibration curves for the soils.

Also shown on Figure 10 are the previously described tolerance limits. All of the test data points tend to fall within or very close to these limits except for two points to the left of the curve. From standard compaction test data, it was found that these soils were in a state of relatively low compaction in the field while the rest of the tested soils were compacted to greater than 80 percent of maximum density. It is felt that the sand cone densities for the loose materials were probably in error due to the nature of the deposit and were therefore not included in the calculation of the regression line equation for the granular materials. Therefore, Figure 10 actually represents the calibration curve for compacted granular materials. A summary of the compaction data for the granular materials is shown on Table 1.

The moisture count determinations made at the end of each density test were converted into pounds of water per cubic foot of material and

intensity. It can be seen from this graph that the intensity of the

diffusion process would be expected to be high at low temperatures.

Although the measurements of the rate of diffusion are not very accurate

the data show that the rate of diffusion is high at low temperatures

and that it decreases as the temperature increases. This is in agreement

with the theory of diffusion which states that the rate of diffusion is

proportional to the square root of the absolute temperature.

It is also seen from the graph that the rate of diffusion is high at low

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correlated with the nuclear counts by using the relative count procedure. A curve of relative count versus pounds of water per cubic foot of material was plotted as shown by Figure 11.

As can be seen from the data which is plotted according to the Unified Classification System, soil type does not affect the moisture calibration curve for Instrument A. This had been shown previously in the laboratory and a comparison of the field calibration curve with the laboratory curve is shown by Figure 12. As can be seen from the figure, both lines are nearly parallel and only offset from one another to a relatively small degree. This difference is attributed to differences in surrounding conditions which exist between the controlled laboratory and the field.

Also indicated on Figure 11 are tolerable limits of error associated with the moisture gauge. The dashed lines indicate an error of ± 1 percent of moisture content. These limits are based on an average value of dry density of 100 pounds per cubic foot. Therefore, for a moisture content of 15 pounds of water per cubic foot of material at a dry density of 100 pounds per cubic foot the moisture content expressed by the standard moisture determination test is given by the relationship:

$$W = \frac{\# \text{ H}_2\text{O} / \text{ft}^3}{\text{Dry Density}} = \frac{15}{100} = 15\%$$

It is shown by Figure 11 that approximately 80 percent of the moisture data fall within the limits of ± 1 percent based on the average dry density of 100 pounds per cubic foot and that the errant values do not fall into any single soil classification grouping. This verifies the belief that soil type does not influence moisture values using the nuclear gauge.

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Instrument "B"

Fewer data were obtained for both moisture and density gauges for this instrument than were obtained for Instrument A. This was due to a battery failure which took place during the testing period. However, enough data were obtained to establish the results as presented in the following paragraphs.

For the density gauge data, the relative counts obtained from the nuclear gauge were plotted against the field sand cone determined densities as previously described. Figure 3 indicated that pH could be used to distinguish between soil types and the effect of such on density results in much the same manner as was done for Instrument A.

The field data were plotted according to the Unified Classification System and are shown on Figure 13. It is observed from this figure that a large amount of scattering of data exists, and that soil type as defined by the Unified Classification System does not delineate any well defined calibration curves.

The data were then plotted by pH range. This is shown by Figure 14 for soils with pH greater than or equal to 7.3 and by Figure 15 for soils with pH less than or equal to 7.2. These figures show the same type of scattering as was observed on Figure 13. In the case of this instrument no well defined calibration curves were obtained from the use of pH ranges as was suggested by Witczak's study on limestone and quartzite.

It is believed that the scattering shown on Figures 14 and 15 is due to instrument malfunction rather than a procedural error.

The calibration curve for the granular materials tested with Instrument B is shown on Figure 16. The same scattering of data is seen to be in evidence on this graph as was found on Figures 14 and 15. The calibration

curve shown is for the compacted soils and does not include the two test soils whose compaction state in the field were less than 80 percent of optimum.

The plot of daily moisture and density standards is illustrated by Figure 17. The reason for the scattering of density data can be inferred from this graph. The density standards are seen to steadily decrease with date of test indicating instrument malfunction. The use of relative count is used to reduce scattering resulting from small fluctuations in standard count from test to test, but will not reduce the scattering if this variation is extreme as is indicated by Figure 17.

An inquiry was sent to the manufacturer concerning this phenomena of decreasing standards, and they stated it was caused by a failure of one of the transistors in the equipment. The instrument has since been returned to the manufacturer for modifications which will correct this situation.

Due to the marked linearity of the density standards decrease with time, it was felt that possibly some correction factor could be applied to the counts in an attempt to reduce the scattering of data points. However, after studying this idea of applying a correction factor to the density standards, no evident procedure was observed and at this writing no such factor has been developed.

Since the standards varied with time, a plot of relative count versus field sand cone density according to different time ranges was made; this is shown on Figure 18. It was observed that the data fell roughly into three time periods, the early part of the summer, the middle of the summer and the last part of the summer testing period.

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Figure 18 shows the calibration curve for Instrument B using time as a factor and it is observed that a large amount of scattering also exists in this case. However, the data points showing the severest variance from the assumed calibration curve are observed to fall into two general time periods. The data falling to the right of the calibration curve are those collected during the first part of the testing period when the standard count was very high. Those points falling to the left of the curves correspond to tests performed during the latter part of the summer when the standard counts were at their lowest values.

The calibration curve as shown by Figure 18 is not presented as the curve to be used to determine field densities from nuclear counts but is merely the calibration curve representing tests performed during the middle part of the testing period when the standard count was fluctuating around some average value. This curve is shown in an effort to explain or show how the effect of a variation in standard count over a wide range of values might affect the calibration curve for a nuclear instrument and how this variation might be analyzed.

It is important to note that some of the test points taken in all periods of testing fall within tolerable limits of the calibration curve, but that all of the data showing wide degrees of scattering from this line fell into the periods previously noted. Also, this graph represents only test data for soil materials and does not include the data for the granular materials.

The moisture calibration curve for Instrument B is illustrated on Figure 19. The data are plotted according to soil type with relative count plotted against pounds of water per cubic foot of material as determined by the laboratory oven drying moisture test.

It is noted that soil type does not seem to have a pronounced effect on the moisture calibration curve and that the scattering of data is of a random nature as far as soil type is concerned.

The scattering of the moisture data is much less pronounced than that observed for the density gauge, although it is greater than that associated with the moisture gauge for Instrument A. From Figure 17 it is noted that the moisture standards tended to fluctuate around an average value, and did not show a linear decrease with time as observed for the density gauge. However, these fluctuations are much more scattered than was exhibited for Instrument A and it is felt that this is the reason for the greater scattering of data points as shown on Figure 19, as compared to Figure 11.

A comparison of the laboratory determined calibration curve versus the one for the field data is presented on Figure 20. The two curves are seen to be approximately parallel but offset. A comparison of Figure 20 with Figure 12 shows that the same variance in laboratory and field moisture calibration curves existed for both Instruments A and B, and this similarity tends to validate the calibration curves obtained for these instruments.

Instrument "C"

As stated previously, this instrument experienced mechanical malfunctions at the beginning of the test period. Both the moisture and density gauges suffered similar failures and were returned to the manufacturer for repair. Since the gauges were not returned by the manufacturers until late in the summer testing period, insufficient data were collected to present calibration curves for this instrument.

SUMMARY OF RESULTS

A summary of the data obtained for Instruments A and B is presented in Tables 2 and 3. Also, Table 4 summarizes the regression curve equations calculated for the calibration curves for Instrument A. A brief discussion of the results for each individual instrument is presented in the following paragraphs.

Instrument "A"

Three calibration curves were obtained with the density gauge. The materials were divided into two broad categories, (1) fine grained soils and (2) granular materials. A single calibration curve was determined for the granular materials (Figure 10). In the case of the fine grained soils, two calibration curves were computed. These are shown on Figures 7 and 8 and are based on the pH value of the soil.

The moisture calibration curve is shown by Figure 11. The moisture calibration curve was found to be independent of soil type. Figure 12 shows a comparison between laboratory and field calibration curves. These are seen to be approximately parallel but offset. It is recommended that the field calibration be used but that this should be checked from time to time.

Instrument "B"

Due to instrument malfunction, a final calibration curve for the density gauge of this instrument is not presented. However, Figure 18 is presented to show a possible calibration curve for the gauge with date of test as the governing criteria.

CHAPTER 1

The first chapter of the book is devoted to the study of the

history of the subject and the development of the theory.

The second chapter is devoted to the study of the

properties of the functions and the methods of their

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CHAPTER 2

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CHAPTER 3

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The fourth chapter is devoted to the study of the

The moisture calibration curve is shown on Figure 19, the scattering of data is seen to be within a relatively narrow range. A comparison of laboratory and field moisture calibration curves is indicated on Figure 20. The curves are seen to be offset yet approximately parallel indicating that the field calibration curve should be used to determine field moisture content.

Instrument "C"

Due to instrument malfunctions concerning both the moisture and density gauges, insufficient data have been collected to present results for this instrument at this time.

RECOMMENDATIONS

Moisture Gauges

From the field investigation, moisture calibration curves were determined for Instruments A and B, and it was found that these curves were independent of soil type. This verified the results that had been determined in the laboratory study. It was also found that the field calibration curves for the two instruments were slightly different than those determined by laboratory testing. It is recommended that the field calibration curves should be used but that these curves should be checked on each construction job. These instruments can be put to immediate use in the field.

Density Gauges

The laboratory study indicated that soil type influenced the calibration curves for the density gauges. Soil pH was used as an indication of soil type. Two calibration curves were obtained for Instrument A for two pH ranges, greater than or equal to 7.3 and less than or equal to 7.2.

Density calibration curves were not obtained for Instruments B and C due to electronic malfunction of the gauges. Instrument B has been returned to the manufacturer for up-dating and repair at no cost to this project. Likewise, Instrument C can be made operative by making revisions in the electronic circuits.

Instrument A is ready for immediate use in the field. Calibration curves shown in this report can be used but these calibrations should be routinely checked at each construction site. It is recommended that, for the fine grained soils in Indiana, simple pH tests should be used to guide the inspector in selecting the calibration curves for use. The calibration curve contained in this report for granular materials may be used, but it should be routinely checked at each construction site.

Instrument B should be ready for field use as soon as it is returned by the manufacturer. A nominal amount of field checking should be conducted in the field by state forces. These field data used in conjunction with data shown on Figure 18 should permit the establishment of appropriate calibration curves with a minimum amount of effort.

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BY J. W. FULTON

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The first section of the document is a list of names and their corresponding addresses. The names are listed in the first column, and the addresses are listed in the second column. The names are: John Smith, Jane Doe, and Robert Johnson. The addresses are: 123 Main Street, 456 Elm Street, and 789 Oak Street.

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APPENDIX

Figures and Tables



TABLE 1
COMPACTION DATA FOR GRANULAR MATERIALS TESTED

Test No.	Type of Material (Unified Classification)	Max. Std. AASHO Dry Density pcf	*Field Dry Density pcf
D-8	SW	140.0	102.2
D-9	SW	140.0	102.8
D-11	SM	127.1	127.5
D-12	SW	140.0	122.4
D-13	SW-SM	130.5	118.3
D-14	SW-SM	130.5	117.4
M-12	SW-SM	136.0	118.6
M-13	SW-SM	136.0	118.8
M-14	SM-SC	132.6	119.9
M-15	SW-SM	136.0	113.0
M-16	SM	118.8	102.5

*Field Dry Densities Determined Using Data From Sand Cone Test And Oven Dried Moisture Content.

TABLE 2

SUMMARY OF DATA FOR FIELD TESTS PERFORMED

Instrument A

Date	Test No.	Type of Test Area	Wet Density by Sand Cone pcf	Relative Count Density Gage	Water Content %	Relative Count Moisture Gage	pH	Unified Classification
7-9	M-1	Grade	122.1	.225	--	--	9.0	ML-CL
7-10	M-2	Fill	118.2	.224	7.7	.264	8.9	Unc.
7-10	M-3	Waste Area	94.3	.288	13.4	.289	7.6	ML-CL
7-11	M-4	N.G.	83.1	.350	25.4	.500	7.3	ML-CL
7-11	M-5	Borrow Pit	110.1	.270	6.8	.284	8.4	Unc.
7-12	M-6	Fill	121.7	.234	3.5	.151	7.3	ML-CL
7-12	M-7	Waste Area	120.0	.248	6.4	.227	7.0	ML-CL
7-15	D-1	Fill	107.9	.255	12.7	.306	7.7	CL
7-16	D-2	N.G.	90.7	.356	17.1	.355	6.5	ML-CL
7-17	D-3	CL	121.1	.230	9.1	.308	8.2	CL
7-17	D-4	N.G.	84.6	.355	15.2	.292	6.6	CL
7-18	D-5	Waste Area	106.3	.286	27.1	.570	7.2	CH
7-18	D-6	N.G.	92.2	.334	19.2	.374	5.7	ML-CL
7-18	D-7	N.G.	95.0	.328	23.3	.435	6.5	MH



TABLE 2 Cont'd.

7-23	B-1	N.G.	92.7	.300	23.6	.447	5.9	ML
7-23	B-2	N.G.	95.5	.311	18.3	.373	7.3	MH-CH
7-24	B-3	N.G.	108.5	.288	24.8	.507	6.5	ML
7-24	B-4	N.G.	100.1	.320	19.6	.403	4.6	ML
7-24	B-5	Fill	118.8	.258	18.8	.465	4.6	CL
7-25	B-6	N.G.	87.9	.344	9.7	.191	4.8	CL
7-25	B-7	Fill	112.5	.275	21.8	.495	6.0	ML
7-26	B-8	N.G.	122.1	.287	17.8	.393	7.2	ML
7-26	B-9	N.G.	111.1	.264	14.8	.358	6.1	MH-CH
8-1	D-8	Subbase	106.2	.244	3.9	.153	8.2	SW
8-1	D-9	Subbase	108.0	.250	4.95	.204	8.1	SW
8-1	D-10	Fill	121.2	.224	8.3	.257	7.3	CL
8-1	D-11	Subbase	131.8	.234	3.3	.143	7.8	SM
8-2	D-12	Subbase	126.0	.249	3.0	.134	8.2	SW
8-7	M-8	Cut	128.1	.204	7.2	.292	7.7	CL
8-8	D-13	Subbase	122.9	.233	4.0	.188	8.3	SW-SM
8-8	D-14	Subbase	120.8	.247	2.9	.131	8.5	SW-SM
8-9	D-15	Fill	120.9	.246	15.9	.434	6.8	CL
8-12	M-9	N.G.	111.3	.273	12.2	.316	6.6	CL
8-13	M-10	Cut	107.9	.281	18.7	.477	7.1	Unc.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

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10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
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TABLE 2 Cont'd

8-13	M-11	Grade	122.3	.255	17.0	.436	5.9	ML-OL
8-14	M-12	Subbase	124.1	.262	4.8	.148	8.0	SW-SM
8-14	M-13	Subbase	124.3	.259	4.5	.159	8.6	SW-SM
8-14	M-14	Grade	124.0	.253	3.3	.209	9.6	SM-SC
8-15	M-15	Subbase	117.6	.268	4.2	.156	9.4	SW-SM
8-15	M-16	Borrow Pit	107.6	.295	5.0	.165	8.0	SM
8-15	M-17	N.G.	104.9	.295	14.7	.362	7.2	CL
8-16	M-18	N.G.	103.2	.281	5.3	.197	8.1	ML-CL
8-21	M-19	Cut	115.4	.275	11.8	.362	6.5	MH-CH
8-22	M-20	N.G.	107.9	.298	17.0	.370	6.9	CL
8-22	M-21	Cut	123.9	.250	12.4	.378	7.2	CL
8-23	M-22	N.G.	109.1	.287	12.0	.317	6.4	CL
8-27	B-11	N.G.	94.3	.314	17.4	--	7.3	MH-CH
8-28	B-14	N.G.	92.4	.330	14.7	--	4.6	ML
8-28	B-15	N.G.	107.8	.276	15.8	--	5.6	ML
8-29	B-16	Fill	114.6	.291	15.5	--	5.2	CL
8-29	B-17	Fill	85.1	.352	7.0	--	5.3	Unc.
8-29	B-18	N.G.	94.6	.350	12.2	.253	5.9	ML
8-29	B-19	N.G.	94.1	.316	15.5	.331	7.3	ML-CL

TABLE 2 Cont'd

8-30	B-20	N.G.	106.5	.337	28.1	.560	6.5	ML
9-4	M-23	Fill	125.9	.246	6.4	.219	8.4	Unc.
9-4	M-24	Cut	113.8	.260	6.0	.242	8.4	CL
9-5	M-25	N.G.	104.6	.279	8.2	.401	7.9	CL
9-5	M-26	Cut	115.7	.270	11.7	.183	6.9	Unc.
9-6	M-27	Cut	119.0	.242	--	--	8.4	CL

* N.G. - indicates a natural ground test area

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TABLE 3

SUMMARY OF DATA FOR FIELD TESTS PERFORMED

Instrument B

Date	Test No.	Type of Test Area	Wet Density by Sand Cone pcf	Relative Count Density Gage	Water Content %	Relative Count Moisture Gage	pH	Unified Classification
7-10	M-2	Fill	118.2	1.94	7.7	—	8.9	Uns.
7-10	M-3	Waste Area	94.3	1.97	13.4	.97	7.6	ML-CL
7-11	M-4	N.G.	83.1	2.13	25.4	1.47	7.3	ML-CL
7-11	M-5	Borrow Pit	110.1	1.95	6.8	.89	8.4	Uns.
7-12	M-6	Fill	121.7	1.70	3.5	.555	7.3	ML-CL
7-12	M-7	Waste Area	120.8	1.80	6.4	.83	7.0	ML-CL
7-16	D-1	Fill	107.9	1.65	12.7	1.07	7.7	CL
7-18	D-5	Waste Area	106.3	1.88	27.1	1.43	7.2	CH
7-18	D-6	N.G.	92.2	1.96	19.2	1.10	5.7	ML-CL
7-18	D-7	N.G.	95.0	2.00	23.3	1.31	6.5	PH
7-23	B-1	N.G.	92.7	1.96	23.6	—	5.9	ML
7-23	B-2	N.G.	95.5	1.91	18.3	—	7.3	MH-CH
7-24	B-4	N.G.	100.1	1.96	19.6	—	4.6	ML

TABLE 3 Cont'd

7-25	B-6	No. G.	87.9	1.9%	9.7	.72	4.8	CL
7-25	B-7	Fill	112.5	1.67	21.8	1.39	0.0	ML
7-26	B-9	No. G.	111.1	1.68	14.5	—	6.1	MH-CH
8-1	D-6	Subbase	106.2	1.64	3.9	—	8.2	SW
8-1	D-9	Subbase	108.0	1.63	4.95	.857	8.1	SW
8-1	D-10	Fill	121.2	1.64	8.3	—	7.3	CL
8-1	D-11	Subbase	131.8	1.53	3.3	.702	7.8	SM
8-2	D-12	Subbase	126.0	1.54	3.0	.54	8.2	SW
8-7	M-8	Cut	128.1	1.38	7.2	.973	7.7	CL
8-8	D-13	Subbase	122.9	1.48	4.0	.720	8.3	SW-SM
8-8	D-14	Subbase	120.8	1.62	2.9	.730	8.5	SW-SM
8-9	D-15	Fill	120.9	1.56	15.9	1.38	6.8	CL
8-12	M-9	No. G.	111.3	1.62	12.2	1.05	6.6	CL
8-13	M-10	Cut	107.9	1.68	18.7	1.45	7.1	Une.
8-13	M-11	Grade	122.3	1.56	17.0	1.30	5.9	ML-CL
8-14	M-12	Subbase	124.1	1.56	4.8	.501	8.0	SW-SM
8-14	M-13	Subbase	124.3	1.63	4.5	.663	8.6	SW-SM

TABLE 3 Cont'd

S-14	M-14	Grade	124.0	1.51	3.3	.755	9.6	SN=SC
S-15	M-15	Subbase	117.6	1.64	4.2	.569	9.4	SN=SM
S-15	M-16	Borrow P42	107.6	1.78	5.0	.715	8.0	SM
S-15	M-17	N.G.	104.9	1.71	14.7	1.12	7.2	CL
S-16	M-18	N.G.	103.2	1.75	5.3	.690	8.1	ML=CL
S-21	M-19	Cut	115.4	1.60	11.8	1.142	6.5	ML=CH
S-22	M-20	N.G.	107.9	1.72	17.0	1.183	6.9	CL
S-22	M-21	Cut	123.9	1.63	12.4	1.157	7.2	CL
S-23	M-22	N.G.	109.1	1.67	12.0	—	6.4	CL
S-27	B-10	N.G.	92.9	1.68	—	—	5.9	ML
S-27	B-11	N.G.	94.3	1.73	17.4	1.24	7.3	ML=CH
S-27	B-12	N.G.	99.3	1.87	20.1	1.25	6.5	ML
S-27	B-13	N.G.	106.2	1.72	8.9	.76	4.8	CL
S-28	B-14	N.G.	92.4	1.712	14.7	1.00	4.6	ML
S-28	B-15	N.G.	107.8	1.66	15.8	1.20	5.6	ML
S-29	B-16	Fill	114.6	1.58	15.5	1.27	5.2	CL

一、關於本會之組織及職權

二、關於本會之經費及財產

三、關於本會之業務及活動

四、關於本會之紀律及懲戒

五、關於本會之附屬機構

六、關於本會之其他事項

七、關於本會之修訂及廢止

八、關於本會之生效日期

九、關於本會之解释权

十、關於本會之其他事項

TABLE 3 Cont'd

8-29	B-17	Fill	85.1	1.77	7.0	.652	5.3	Unc.
8-29	B-18	N.G.	94.6	1.76	12.2	.871	5.9	ML
8-29	B-14	N.G.	94.1	1.60	15.5	1.07	7.3	ML-CL
8-20	D-20	N.G.	106.5	1.765	23.1	=	6.5	ML
9-4	M-23	Fill	125.9	1.51	6.4	.730	8.4	Unc.
9-4	M-24	Cut	113.8	1.615	6.0	.855	8.4	CL
9-5	M-25	N.G.	104.6	1.56	8.2	=	7.9	CL
9-5	M-26	Cut	115.7	1.595	11.7	.713	6.9	Unc.

TABLE 4

REGRESSION LINE EQUATIONS FOR CALIBRATION CURVES
FOR INSTRUMENT A

<u>Type of Gage</u>	<u>Soil Type</u>	<u>Figure Number</u>	<u>Equation*</u>
Density	Coarse Sand	1	$Y = .342 - .0019X$
Density	Sandy Gravel	1	$Y = .364 - .0019X$
Density	Ph : 7.3	7	$Y = .348 - .0028X$
Density	Ph : 7.2	8	$Y = .364 - .0026X$
Density	Granular Materials	10	$Y = .403 - .0035X$
Moisture	All Soil Types	11	$Y = .093 + .0195X$

Y = Average Relative Count - Obtained from the average of six standard counts and four test counts

X = Unit Weight of Soil

* Least Squares Regression Line, Where X is the Independent Variable

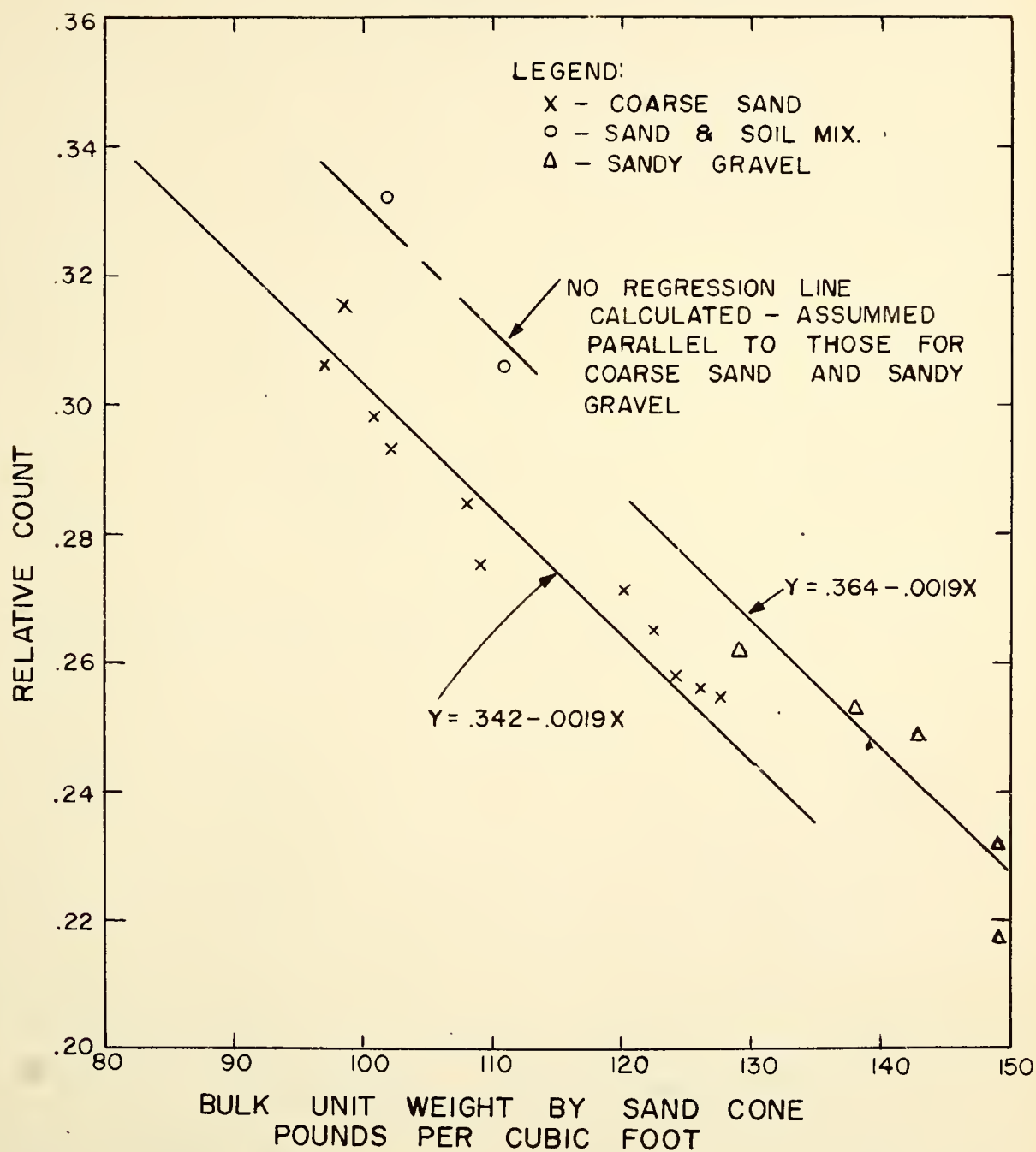


FIG. 1 LABORATORY DENSITY CALIBRATION CURVE
SHOWING SOIL TYPE VARIATION (FROM
PROGRESS REPORT NO. 8) — INSTRUMENT A

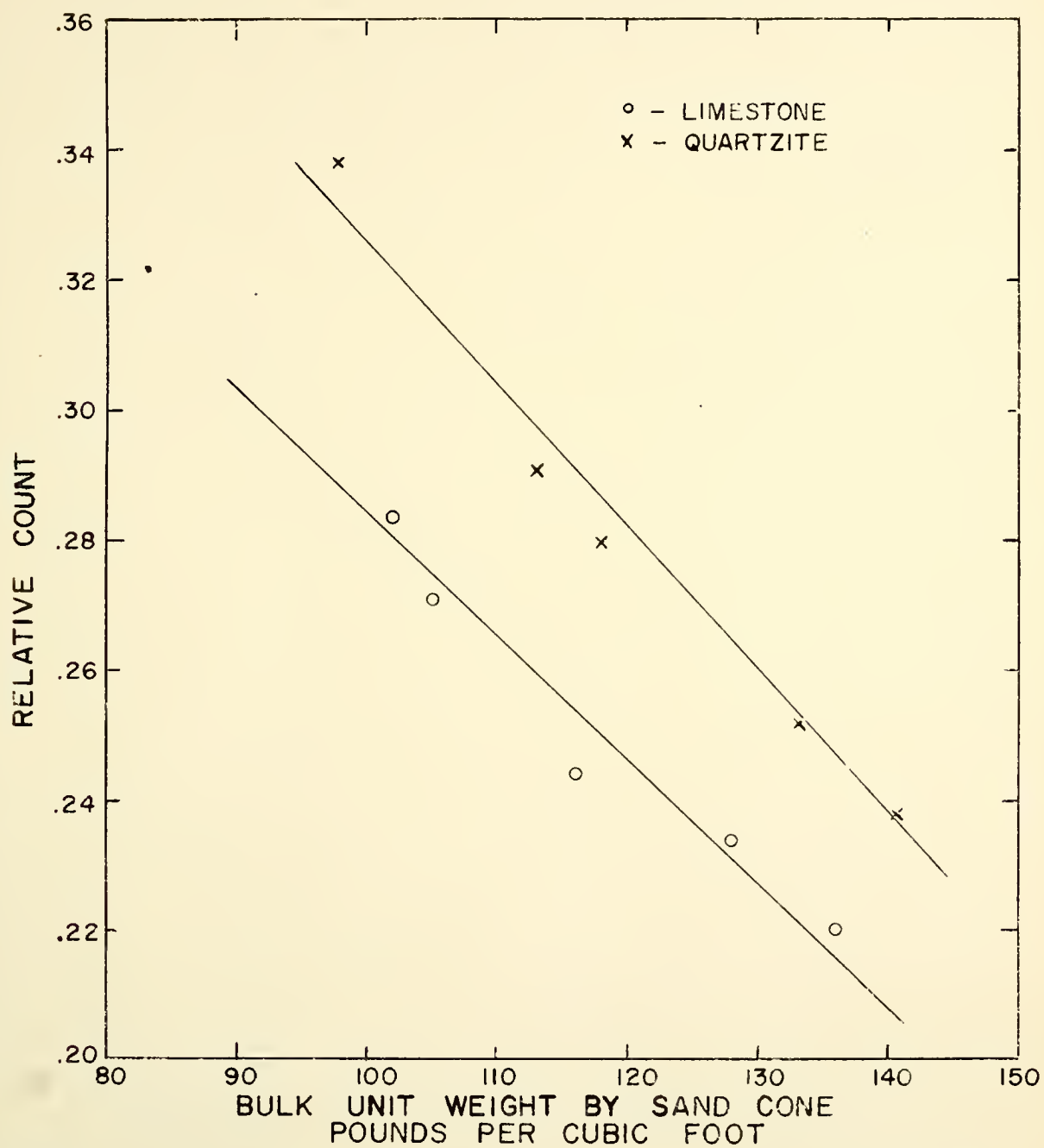


FIG. 2 LABORATORY DENSITY CALIBRATION CURVE FOR
SELECTED LIMESTONE AND QUARTZITE MATERIALS
(FROM WITCZAK) — INSTRUMENT A

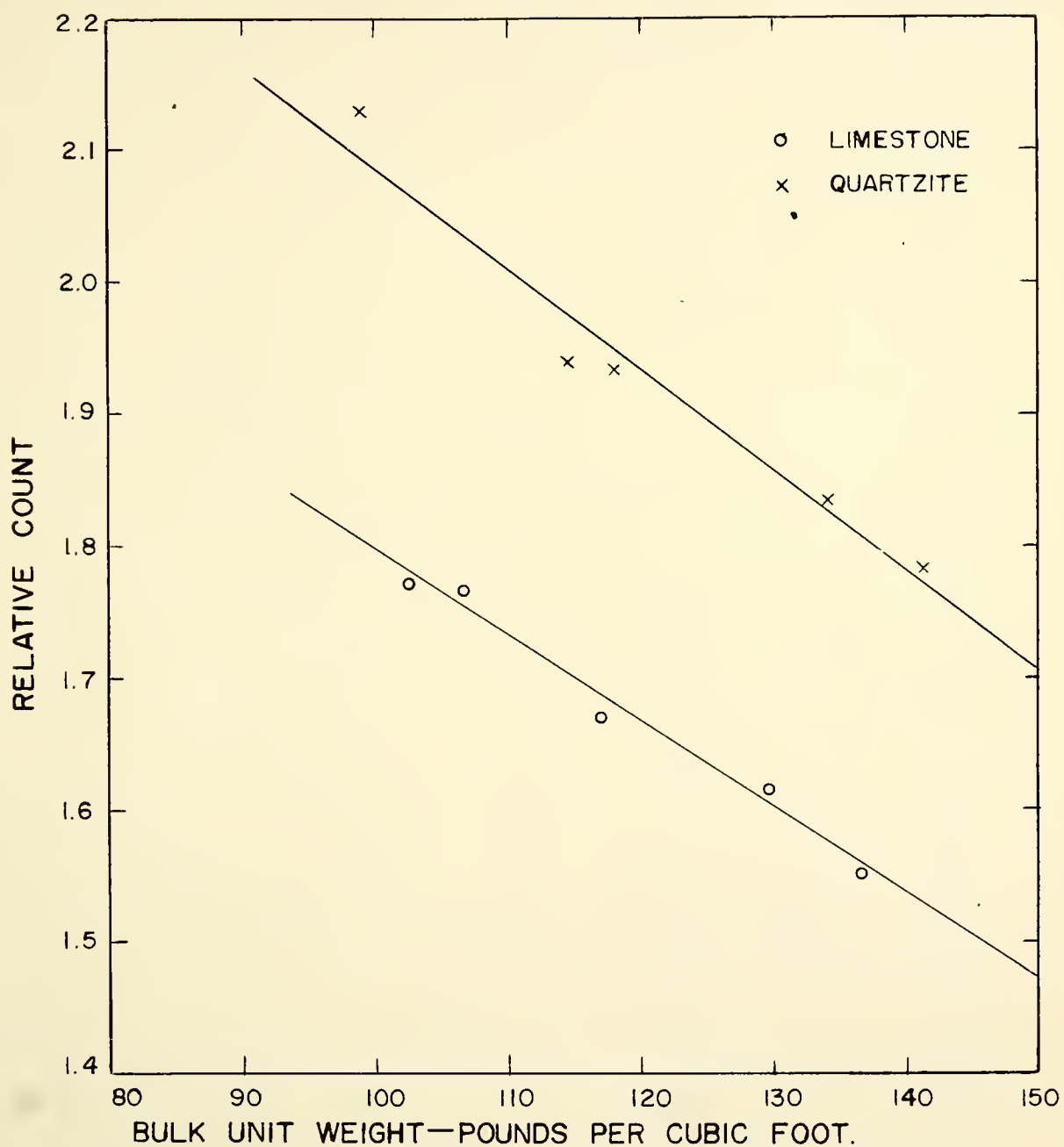


FIG. 3 LABORATORY DENSITY CALIBRATION CURVE FOR LIMESTONE AND QUARTZITE MATERIALS. INSTRUMENT B (FROM WITCZAK).

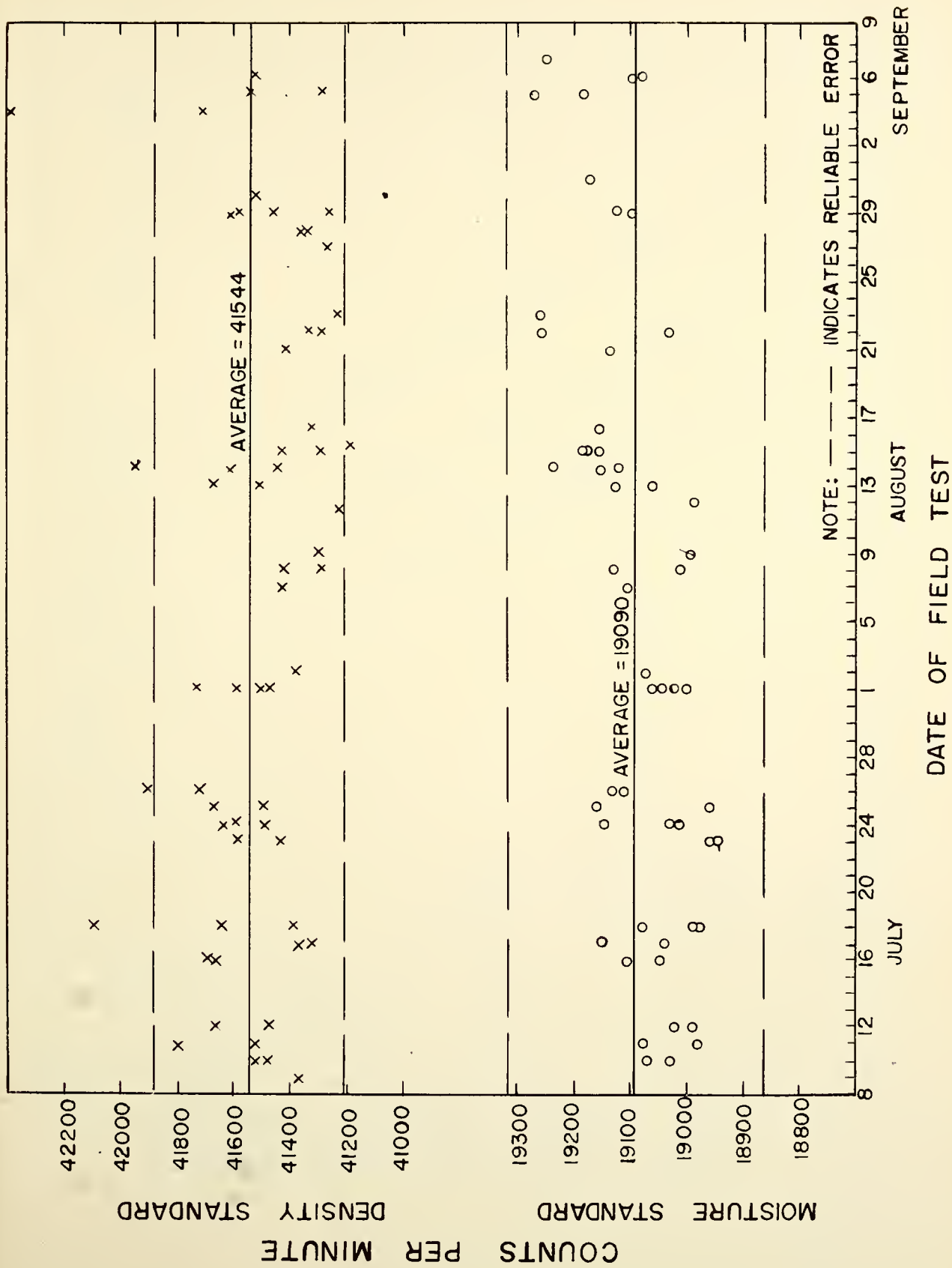


FIG. 4 VARIABILITY OF STANDARD COUNTS — INSTRUMENT A

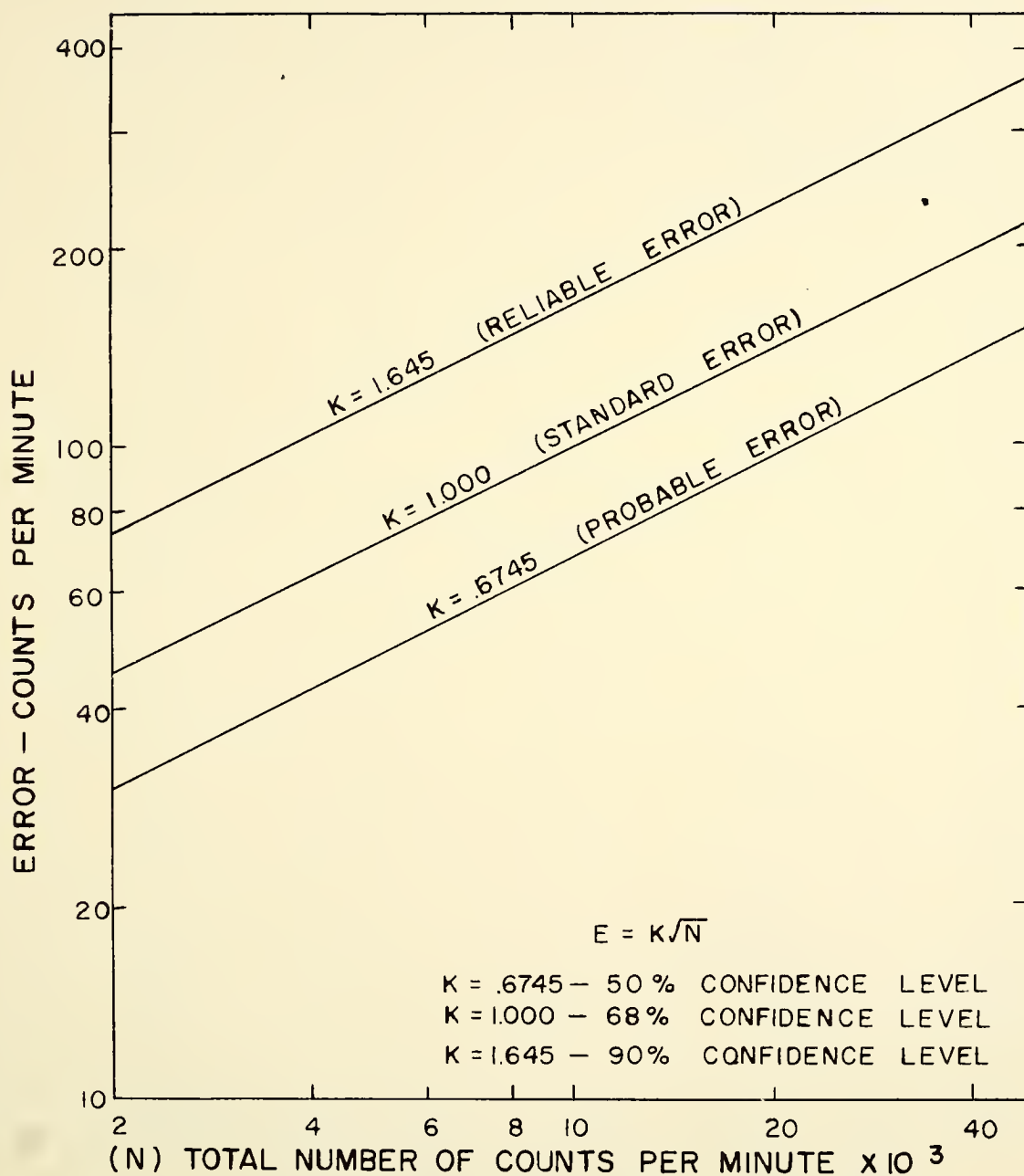


FIG. 5 VARIOUS ERROR SYSTEMS ASSOCIATED WITH RADIATION INTENSITY LEVELS FOR CORRESPONDING CONFIDENCE LIMITS

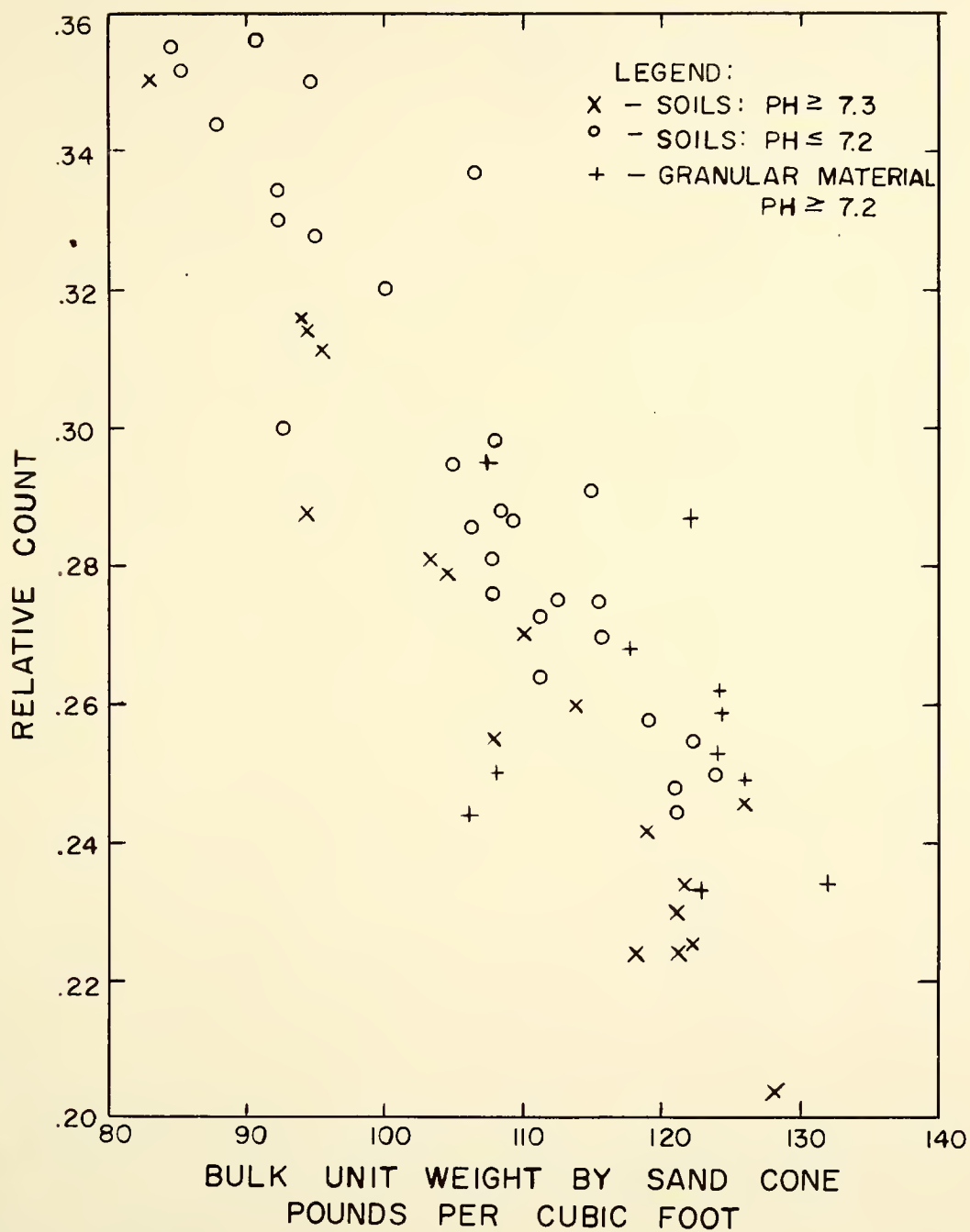


FIG. 6 FIELD DENSITY DATA FOR ALL SOILS
INSTRUMENT A



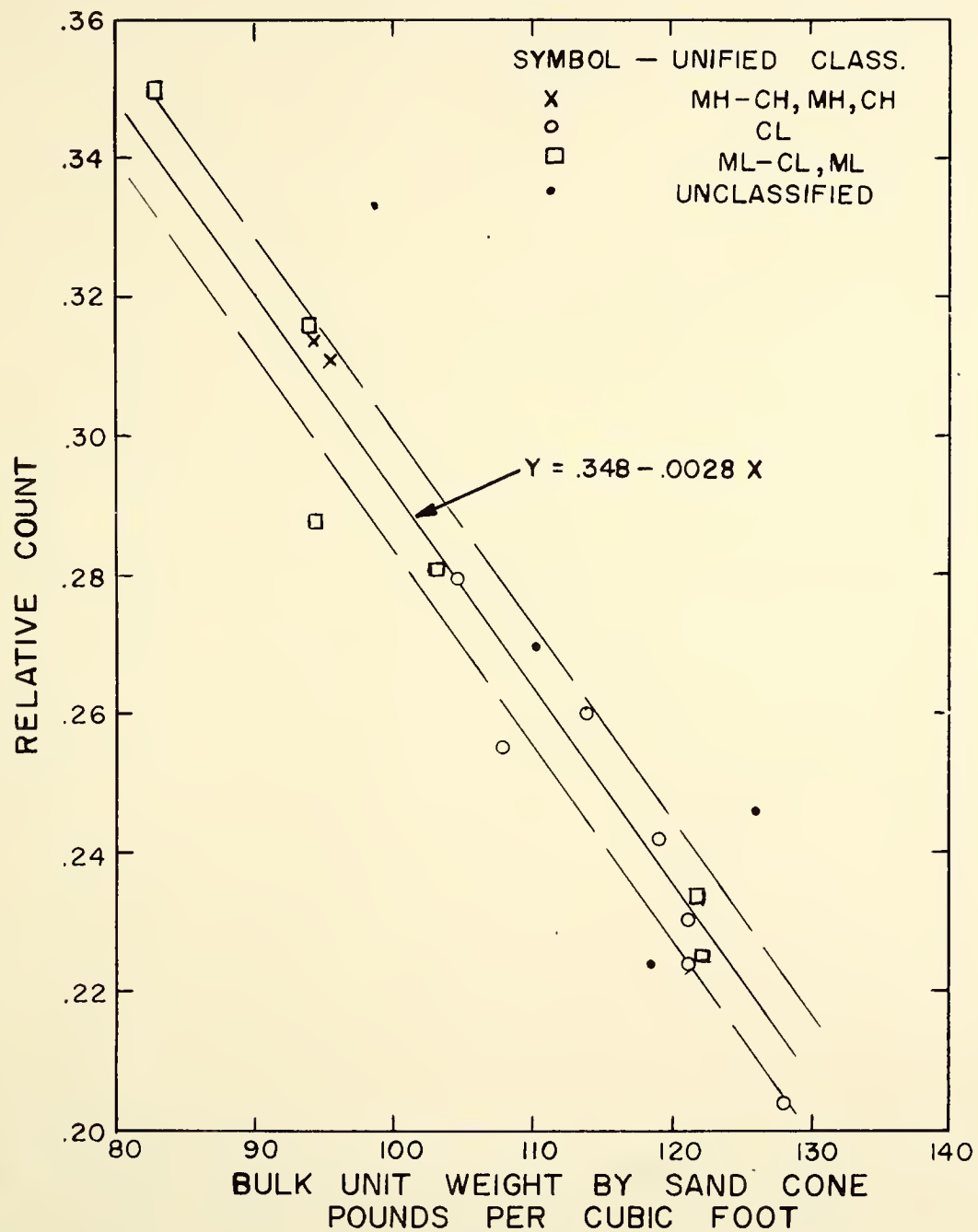


FIG. 7 DENSITY CALIBRATION CURVE FOR FIELD DATA — SOILS WITH $PH \geq 7.3$ — INSTRUMENT A



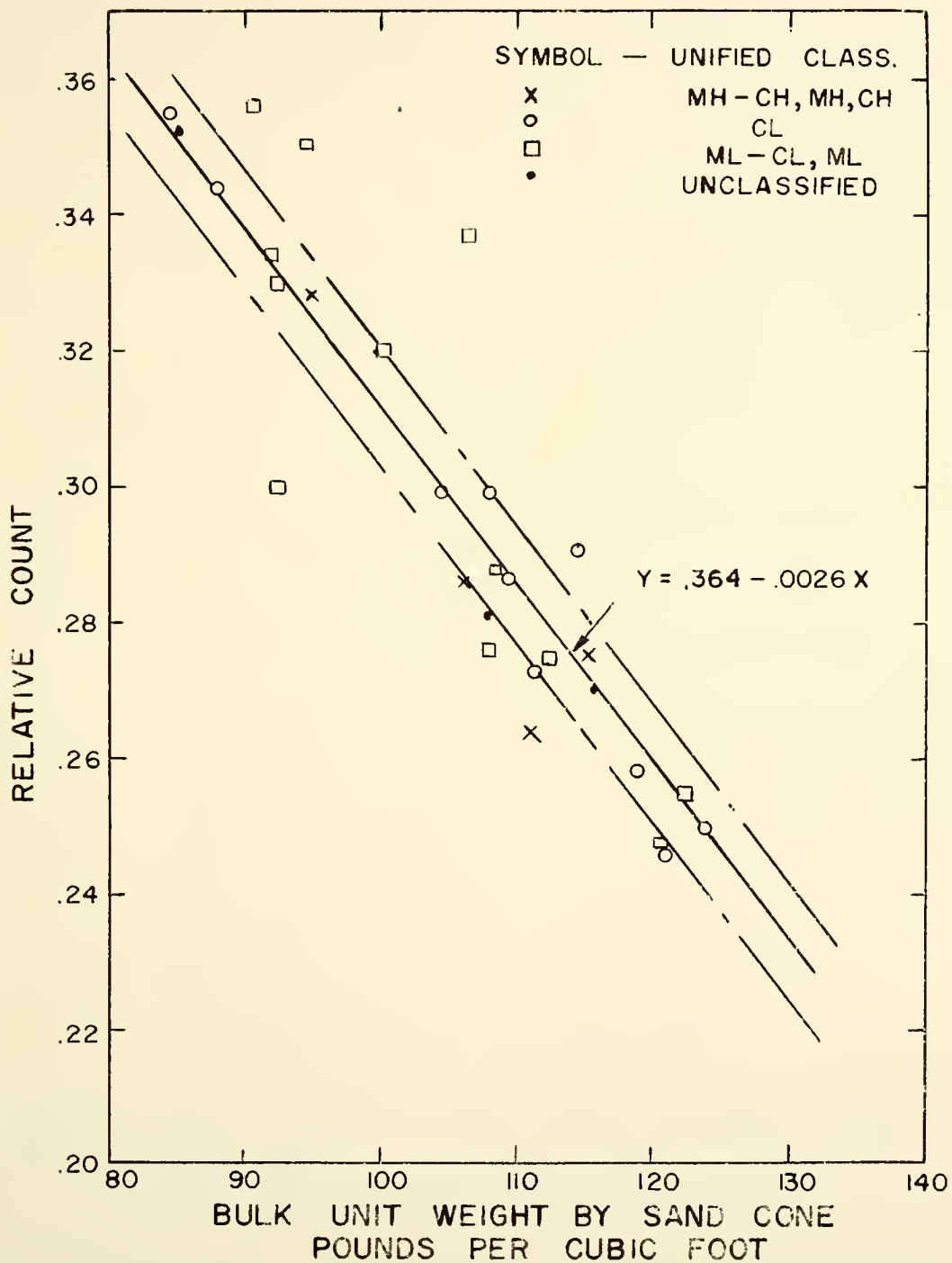


FIG. 8 DENSITY CALIBRATION CURVE FOR FIELD DATA — SOILS WITH $PH \leq 7.2$ — INSTRUMENT A



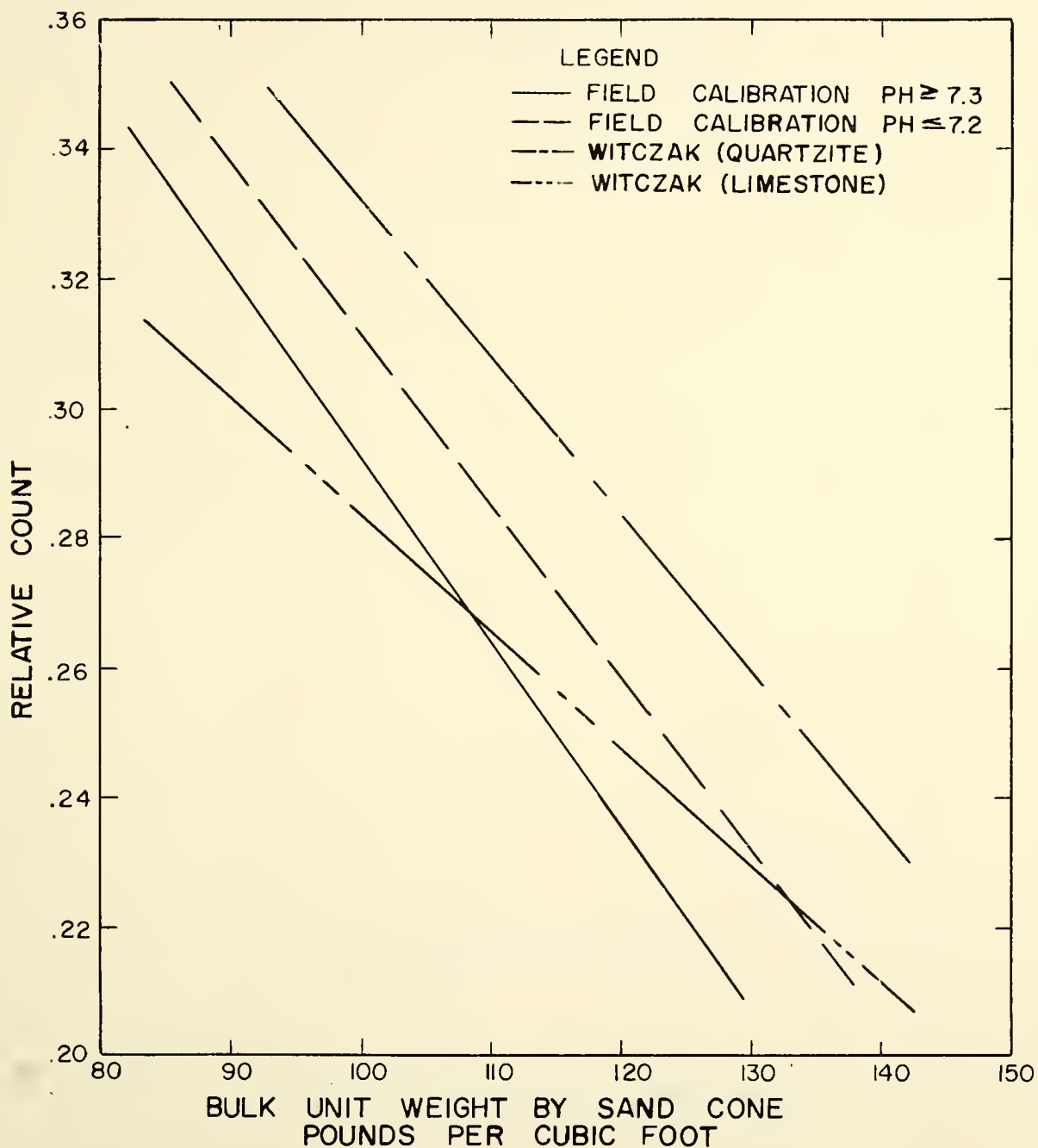


FIG. 9 COMPARISON OF VARIOUS DENSITY CALIBRATION CURVES — INSTRUMENT A

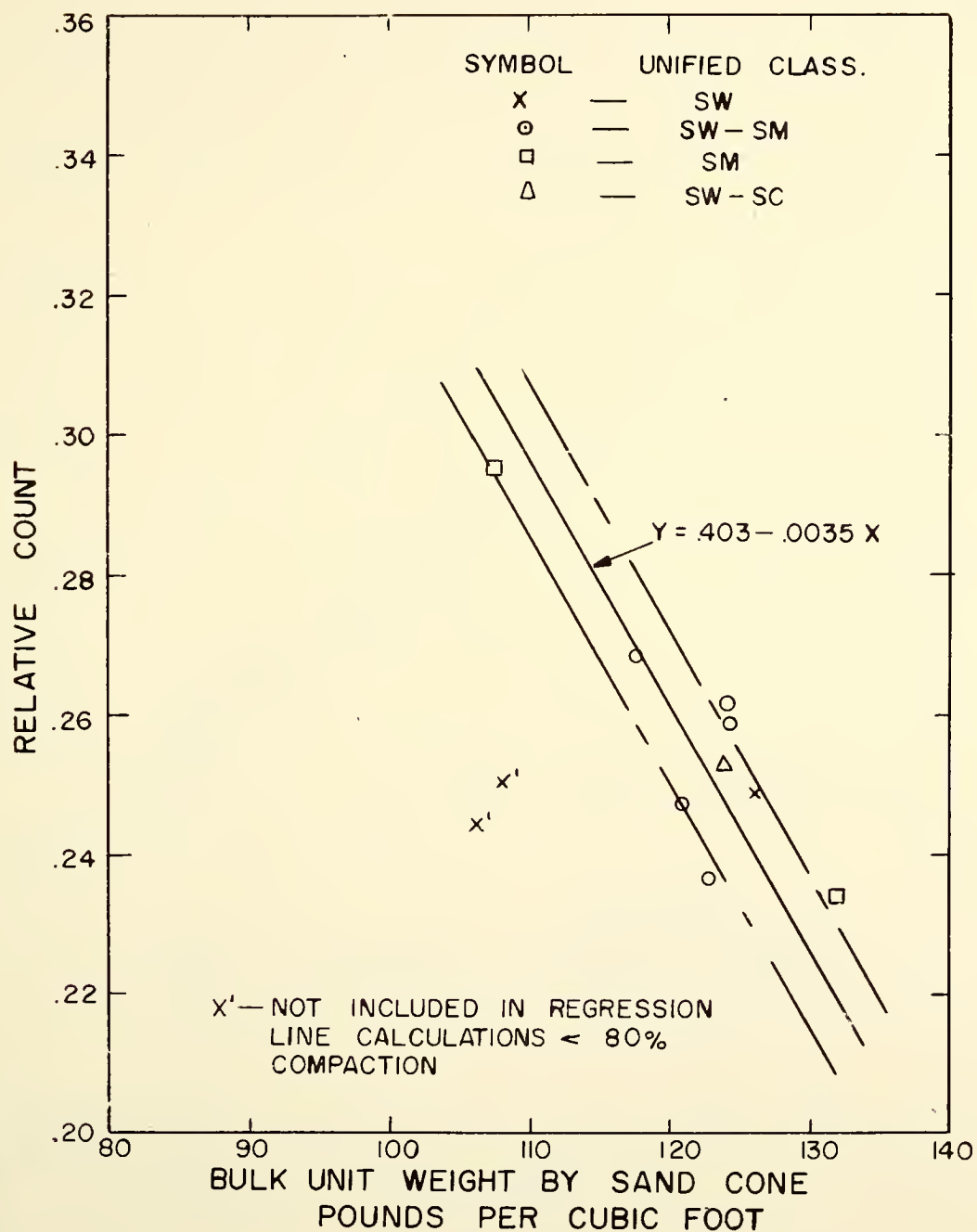


FIG. 10 DENSITY CALIBRATION CURVE FOR FIELD DATA — GRANULAR SOILS — INSTRUMENT A

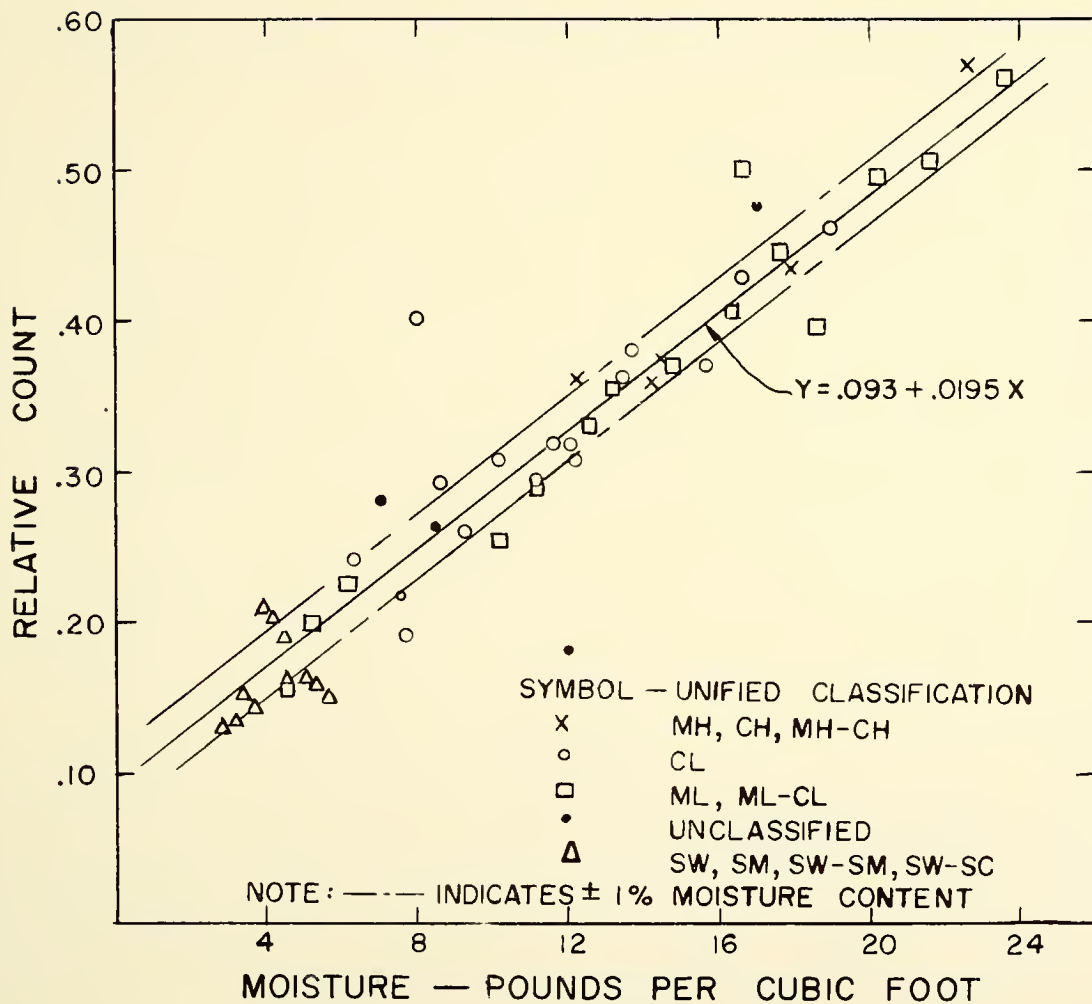


FIG. II MOISTURE CALIBRATION CURVE FOR FIELD DATA — INSTRUMENT A

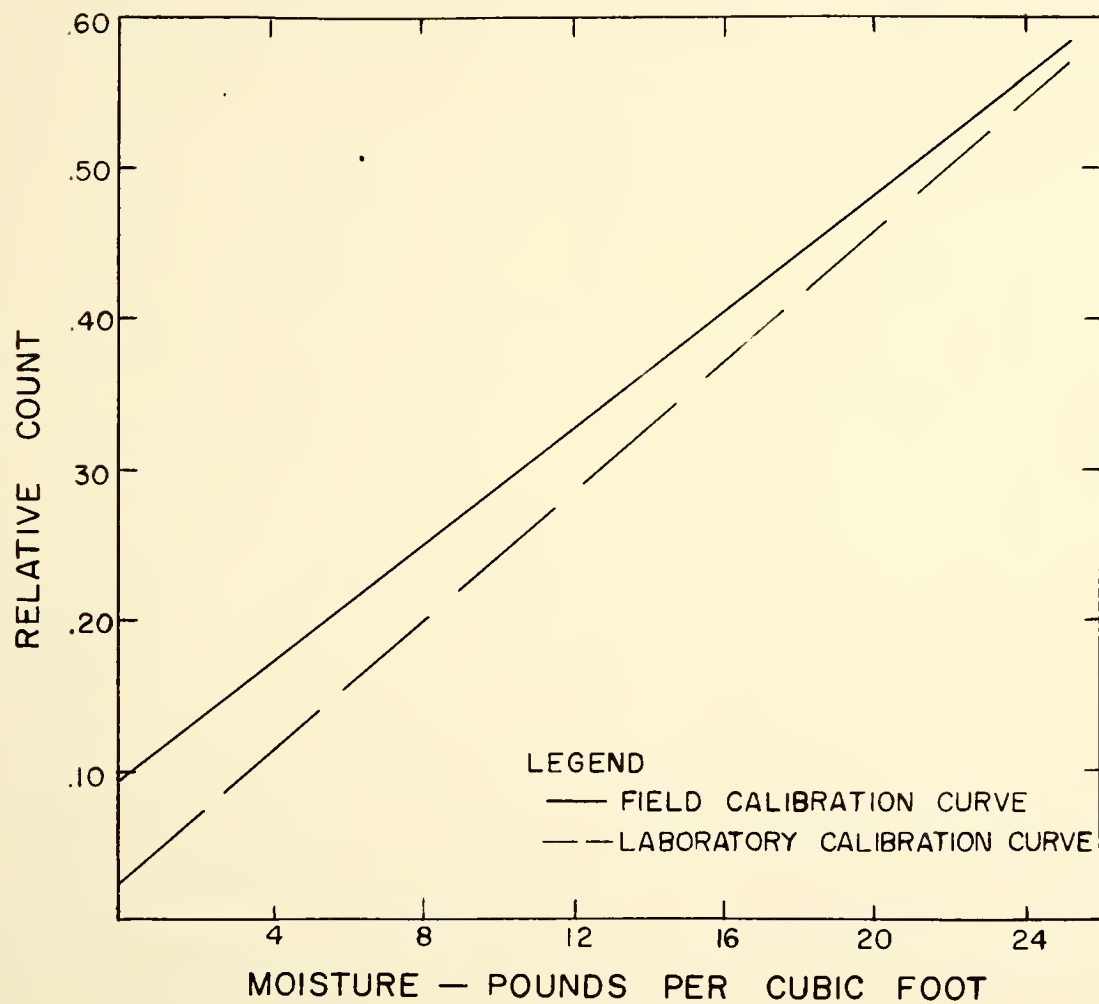


FIG. 12 COMPARISON OF LABORATORY AND FIELD
MOISTURE CALIBRATION CURVES
INSTRUMENT A

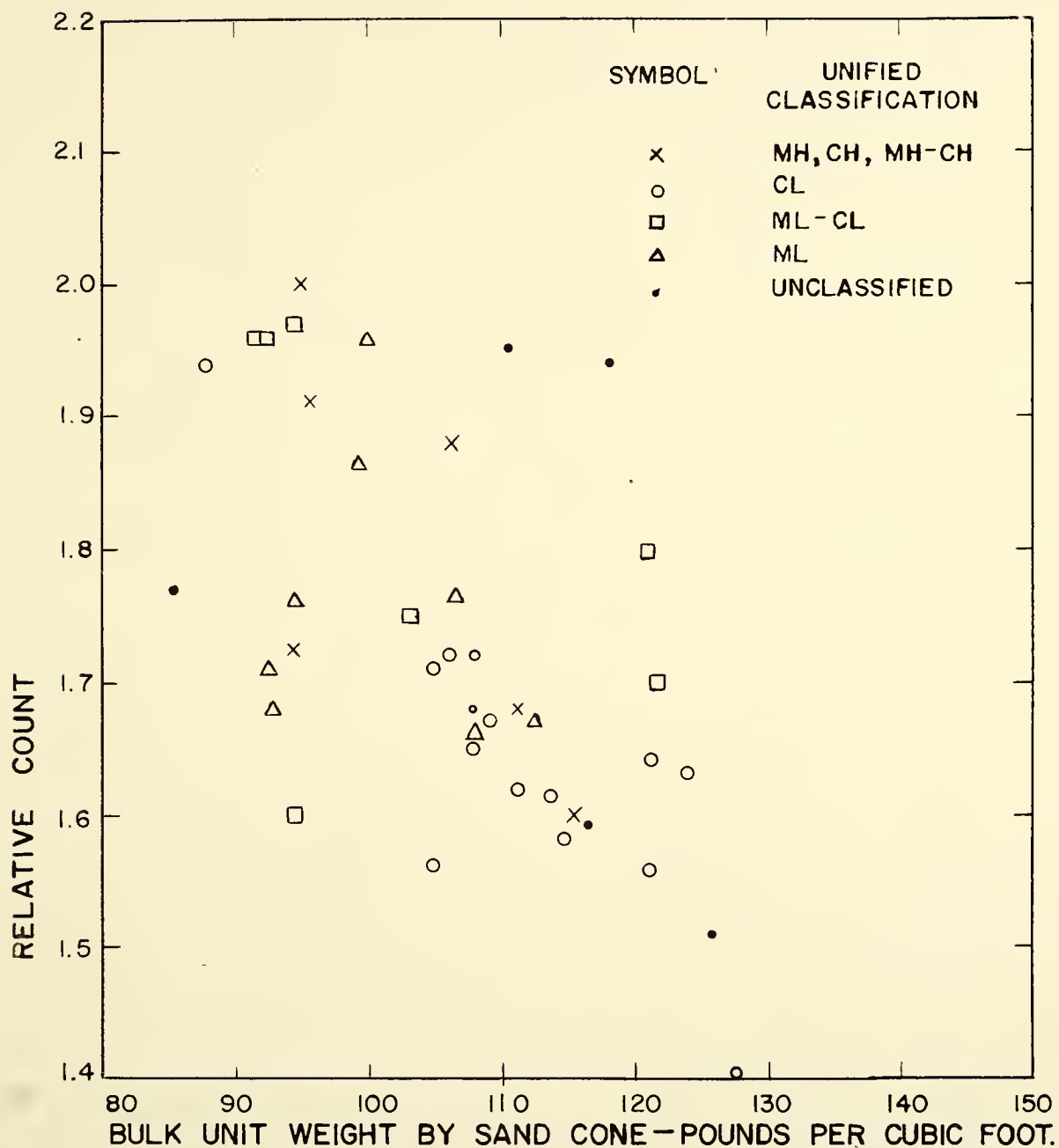


FIG. 13 FIELD DENSITY DATA FOR ALL SOILS (EXCLUDING GRANULAR MATERIALS).—INSTRUMENT B.



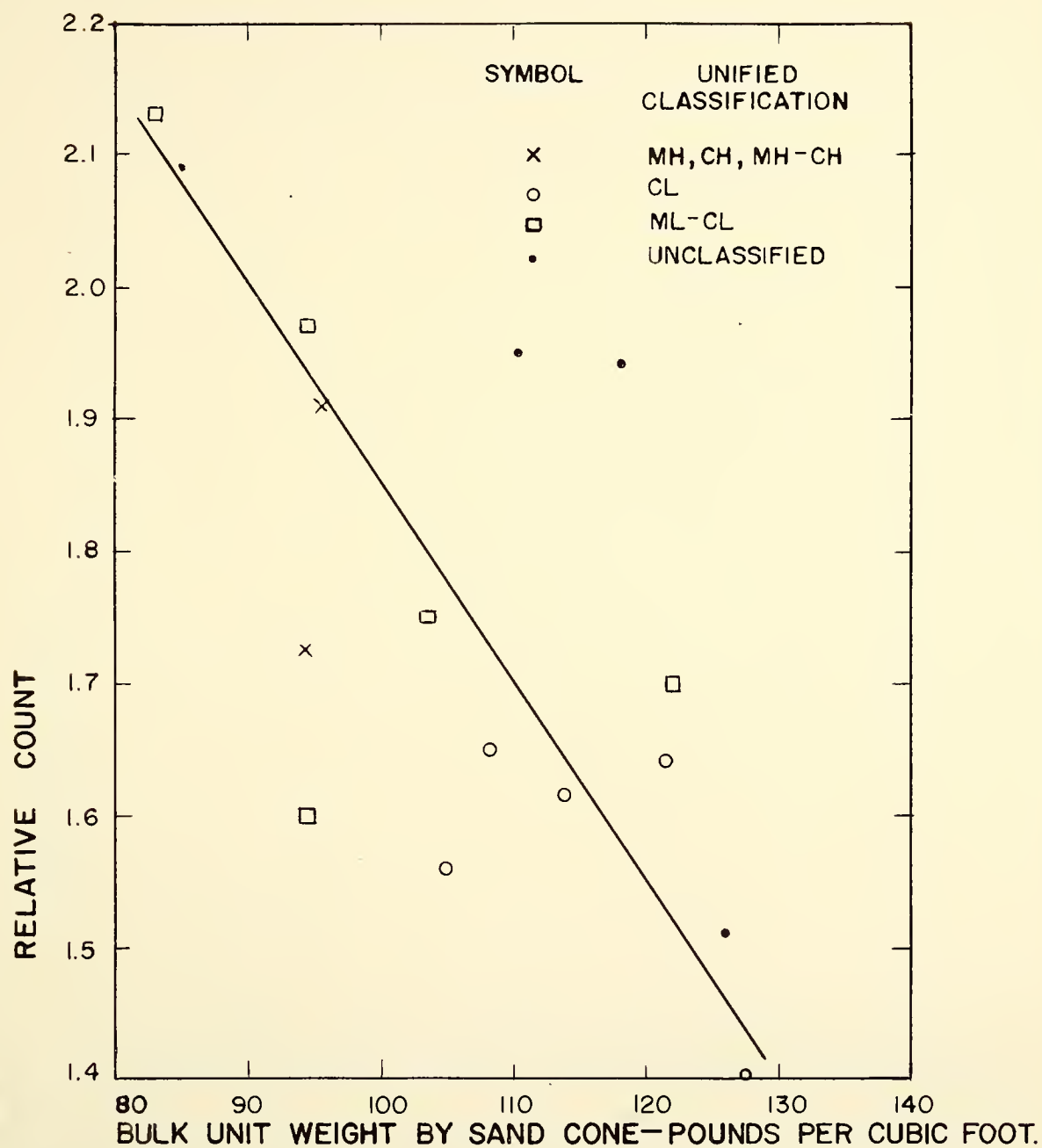


FIG. 14 DENSITY CALIBRATION CURVE FOR FIELD DATA
SOILS WITH $PH \geq 7.3$.—INSTRUMENT B.



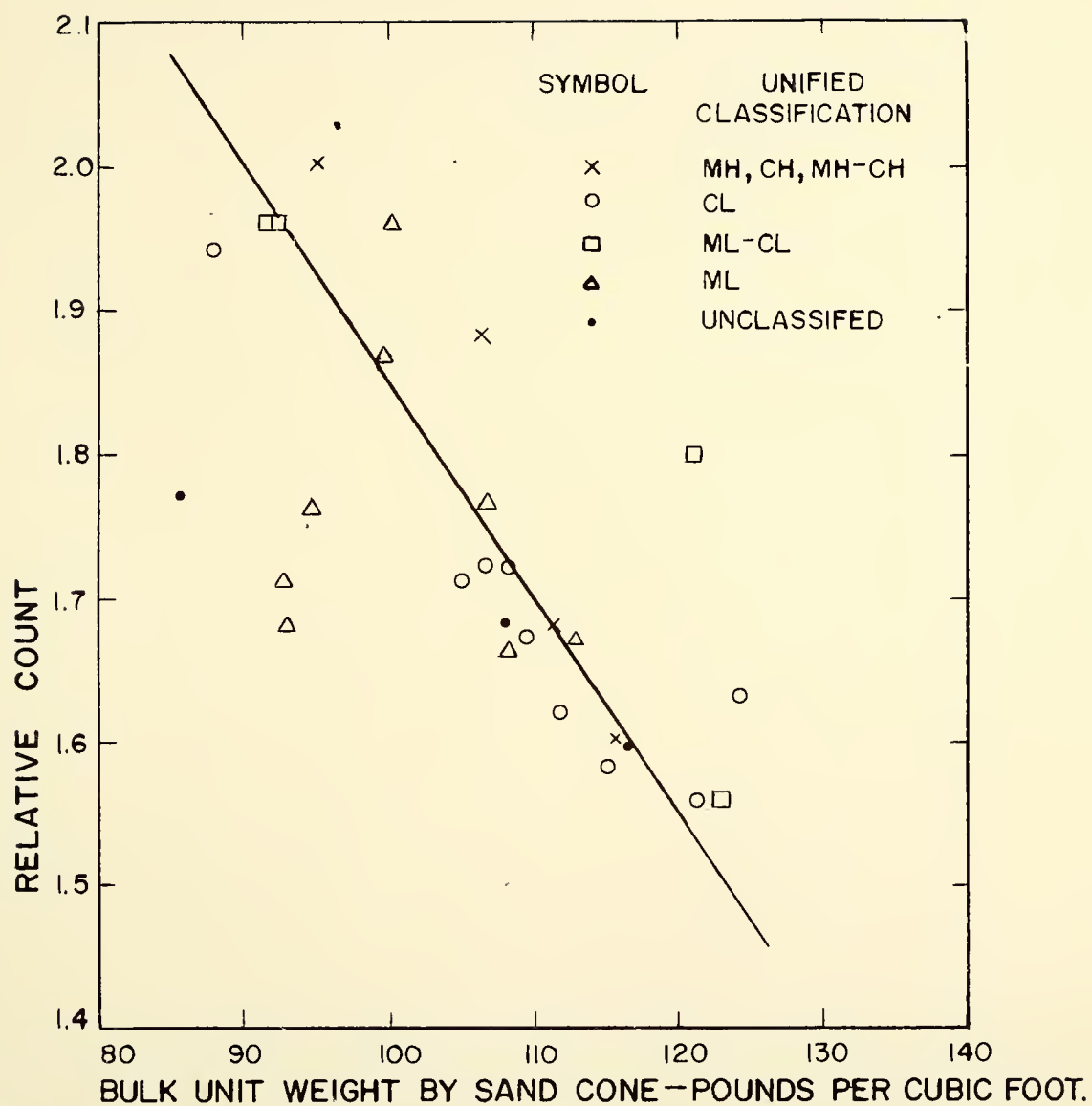


FIG. 15 DENSITY CALIBRATION CURVE FOR FIELD DATA
SOILS WITH $PH \leq 7.2$.—INSTRUMENT B.



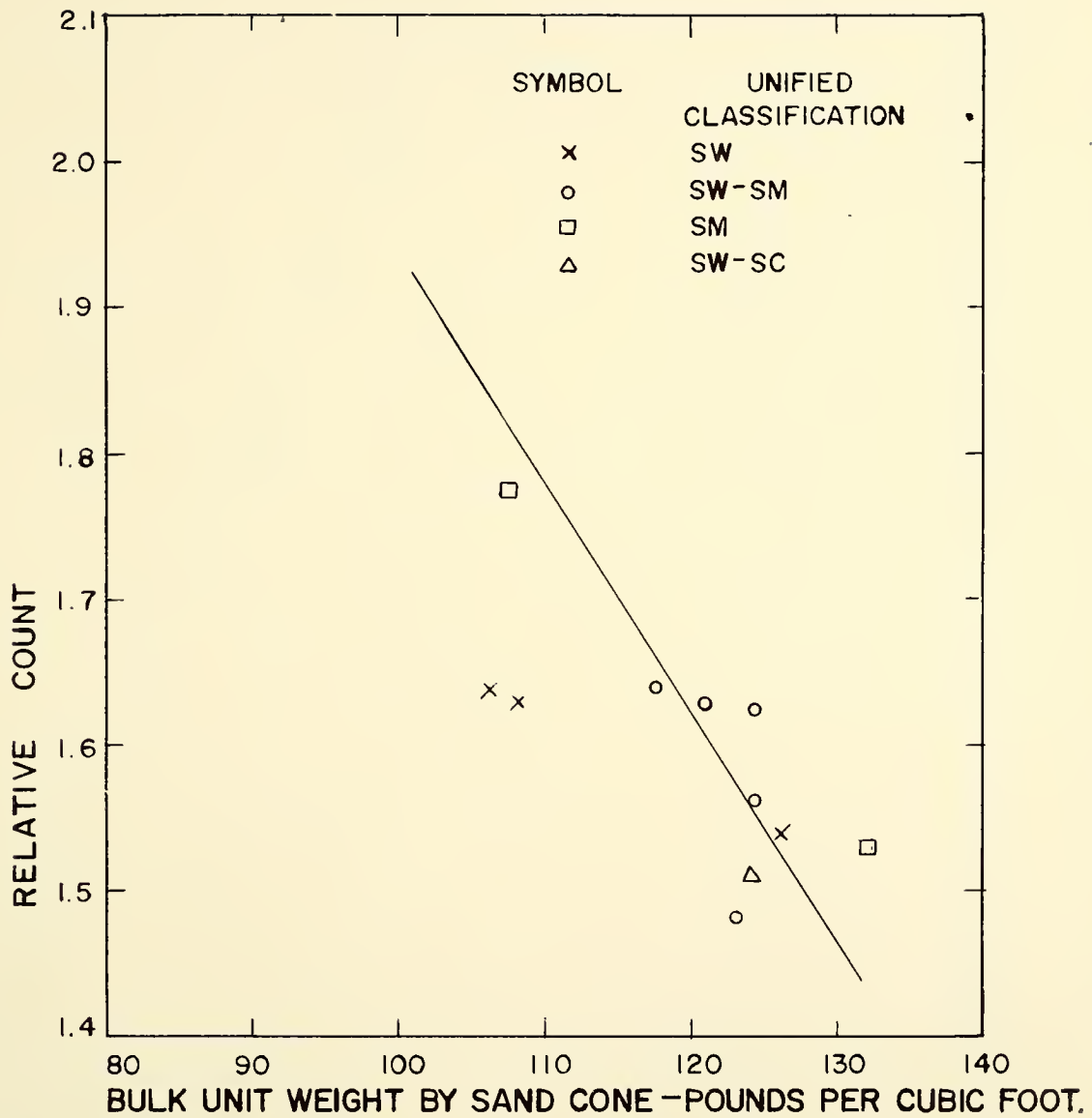


FIG. 16 DENSITY CALIBRATION CURVE FOR FIELD DATA GRANULAR SOILS.-INSTRUMENT B.



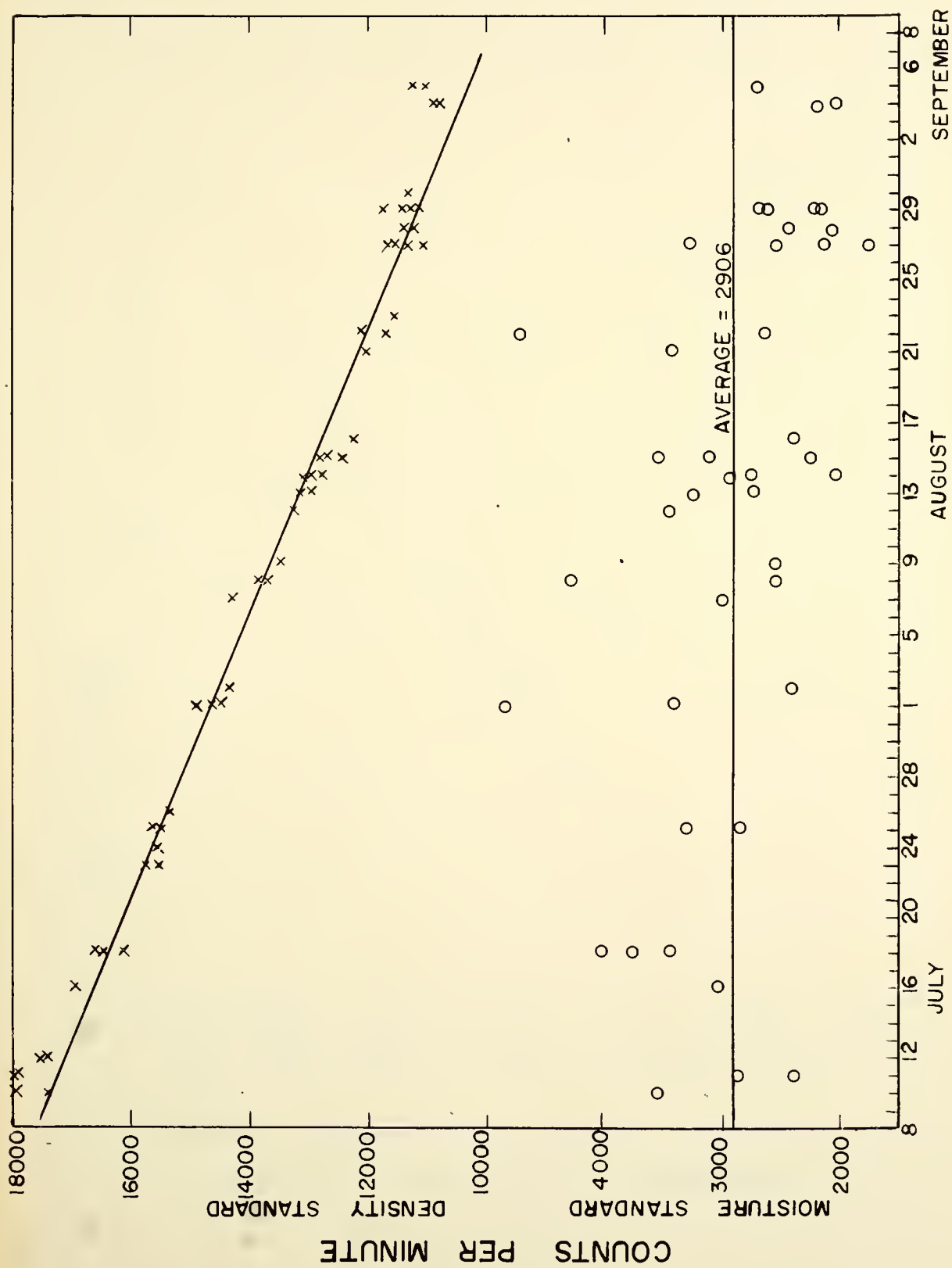


FIG. 17 VARIABILITY OF STANDARD COUNTS — INSTRUMENT B

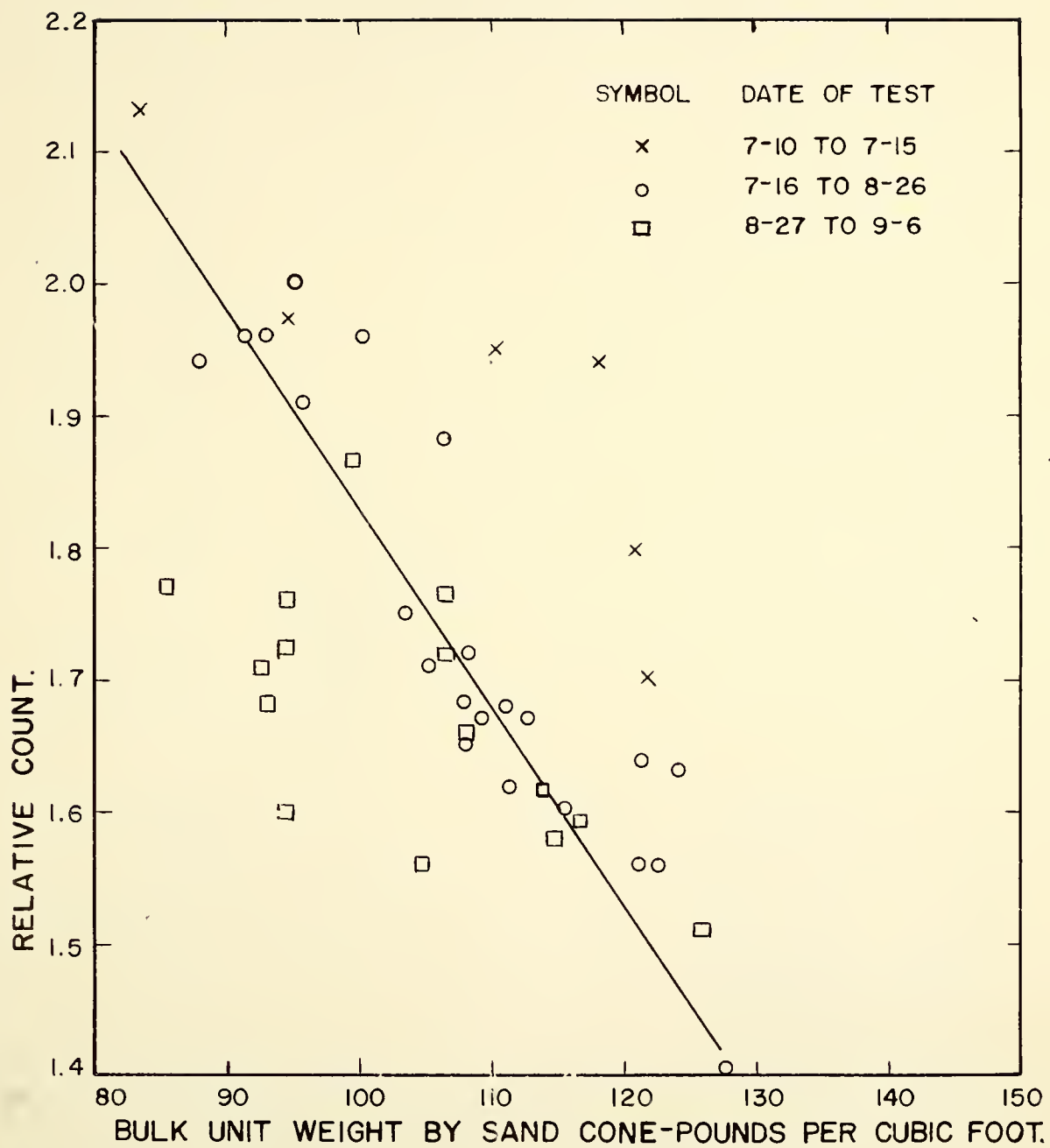


FIG. 18 DENSITY CALIBRATION CURVE FOR FIELD DATA
BY DATE OF TEST — INSTRUMENT B

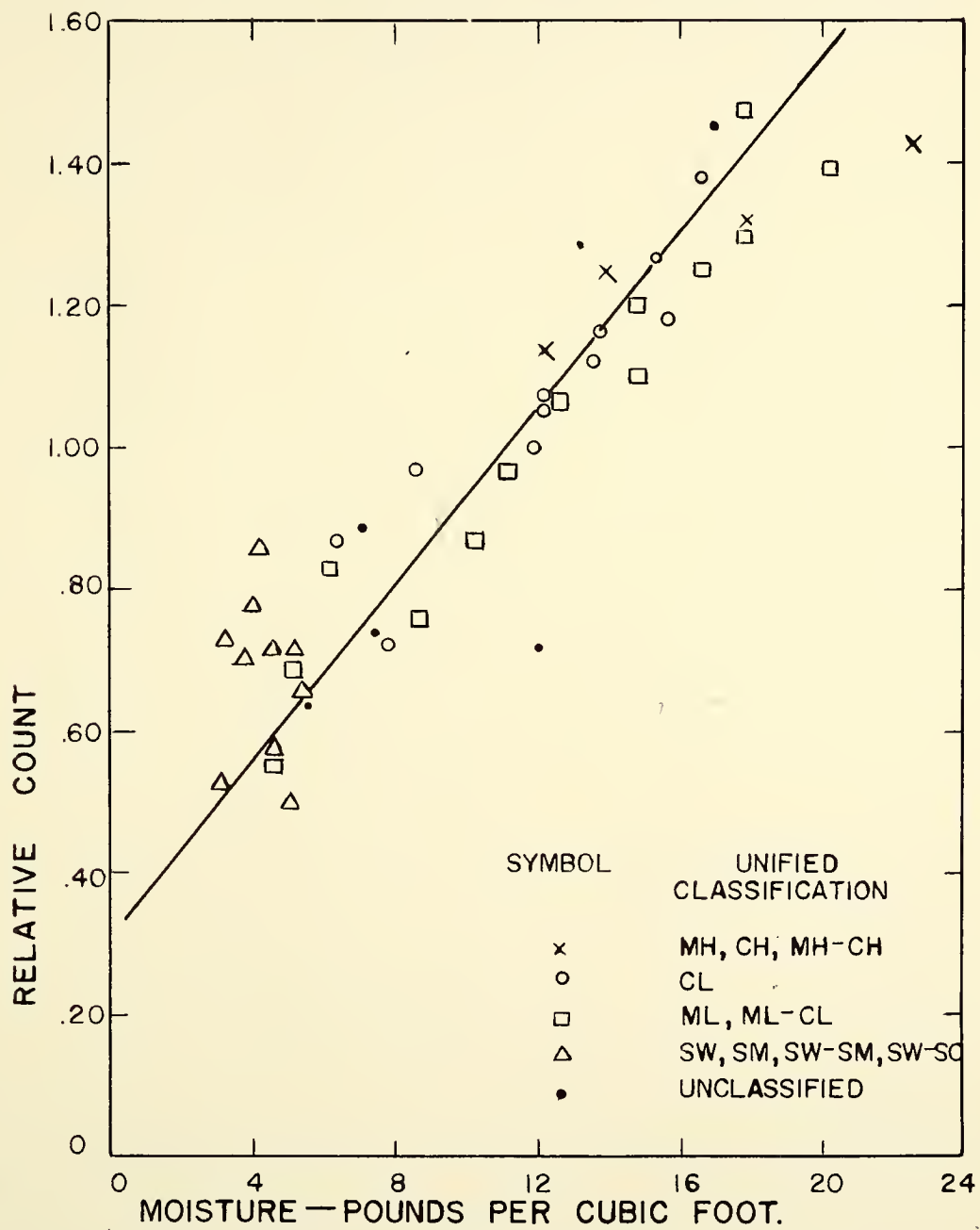


FIG. 19 MOISTURE CALIBRATION CURVE FOR FIELD DATA.—INSTRUMENT B.

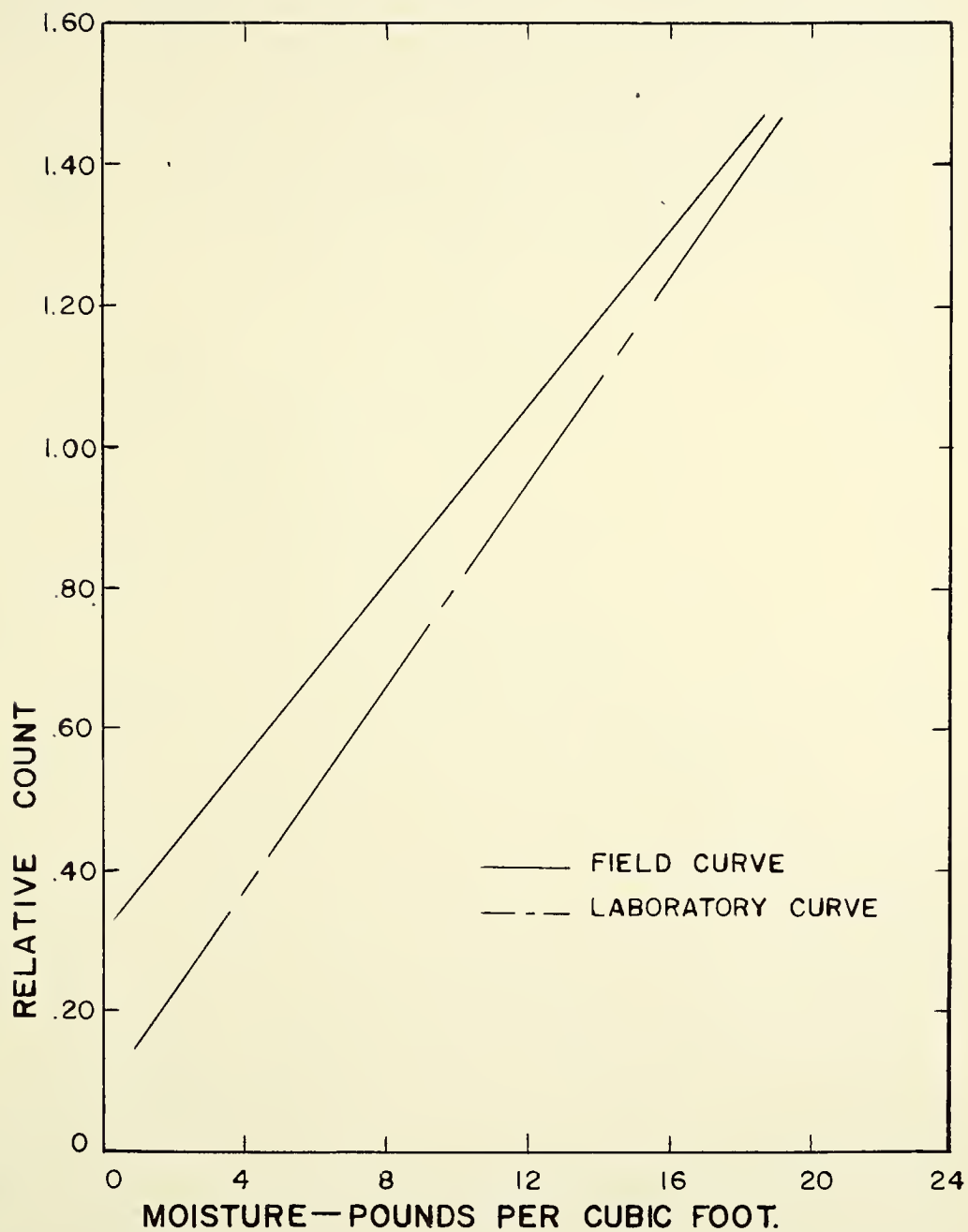


FIG. 20 COMPARISON OF LABORATORY AND FIELD
MOISTURE CALIBRATION CURVES.
INSTRUMENT B.



